Vol. XLIV. DECEMBER. 1900.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

No. 879.

EXPERIMENTS ON THE FLOW OF WATER IN THE SIX-FOOT STEEL AND WOOD PIPE LINE OF THE PIONEER ELECTRIC POWER COMPANY, AT OGDEN, UTAH. SECOND SERIES.

By CHARLES D. MARX, M. Am. Soc. C. E., CHARLES B. WING, Assoc. M. Am. Soc. C. E., and LEANDER M. HOSKINS, C. E.

PRESENTED MARCH 7TH, 1900.

WITH DISCUSSION.

I.—OBJECT AND METHODS.

General Plan.

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* *Transactions*, Am. Soc. C. E., Vol. xl, p. 471.

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The experiments of 1897 upon the steel pipe utilized a length of about 4 400 ft.* In the wood pipe experiments a length of 2 710 ft. was used. The long section of wood pipe above Tunnel No. 7† was not used because the overflow at that point prevented securing static conditions in the pipe above.‡ When the present series of observations was made, it was found possible to stop the overflow by adjusting flash boards properly at the relief shaft and at the dam. Measurements of the loss of head in a length of about 22 700 ft. of the wood pipe above Tunnel No. 7 were therefore made. In addition, a limited number of experiments was made upon the portion of wood pipe used in 1897, as well as a new series upon the steel pipe. A velocity of flow, materially higher than in the preceding series, was secured.

Pressure Measurements.

Six pressure stations, located at the ends of the three portions of pipe above mentioned, were occupied. For convenience of reference, these stations have been designated by the numbers 1, 2, 3, 4, 5 and 6, beginning at the lower end of the steel pipe. Mercury gauges were used at all stations except No. 6, at the upper end of the long section of wood pipe. At this point the pressure was so small that a water piezometer was used.

At Stations Nos. 4 and 5 were placed the gauges used in 1897, and their description need not be repeated here. The only change made in these gauges was the attachment of fixed scales for the purpose of reading the position of the mercury in the reservoirs. The gauges used at Stations Nos. 1, 2 and 3 were open manometers similar to the others, but of a modified design.

In the former experiments, it was found difficult to make the gauges absolutely mercury-tight under the high pressure existing at the power-house. and this difficulty was carefully guarded against in planning the new series. The new gauges were made stronger than the old, and were tested at the highest pressure under which they were to be used. Means were also provided for determining fluctuations in the level

* The length was 4 427 ft. during a part of the series, and 4 367 ft. during the remainder.

† For plan and profile, showing the position of this tunnel, see paper by Henry Goldmark, M. Am. Soc. C. E., *Transactions*, Am. Soc. C. E., Vol. xxxviii, p. 246.

‡ Static readings of the gauges could, of course, be dispensed with if the difference of level between the gauges were known with sufficient exactness. To determine this difference with the requisite accuracy by running a line of levels would have involved such an amount of labor and time as to put this method out of the question.

of the mercury surface in the manometer reservoir, so that, even if leakage of mercury occurred, the observation of the height of the mercury column would not be vitiated. For this purpose the gauge was provided with a glass tube placed vertically at the side of the reservoir and communicating with it at top and bottom (Fig. 1), and by the side of this tube was placed a fixed scale. The position of the

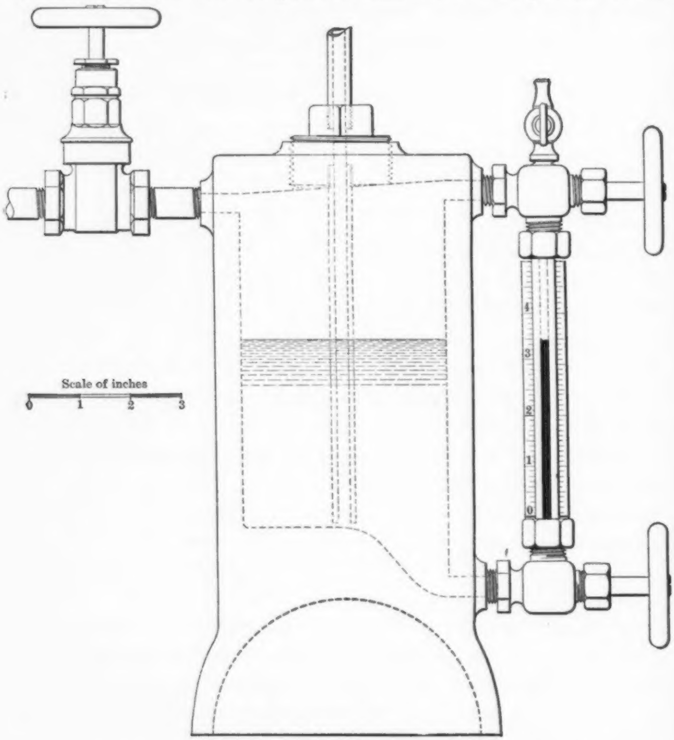


FIG. 1.

top of the mercury in this tube could be read with the same degree of precision as that of the top of the mercury column in the open tube The scales used were in all cases graduated to hundredths of a foot, and the third decimal place was estimated in taking readings.

As in the previous experiments, the long mercury column at Station No. 1 was provided with a water jacket carrying running water, to insure

a uniform temperature. At other stations the temperature was determined by thermometers placed beside the mercury columns.

The specific gravity of the mercury used, in terms of water from the pipe, was determined for the authors in the chemical laboratory of the Ogden Sugar Company, through the courtesy of the Superintendent, Mr. H. T. Dyer. The value adopted was 13.57.*

The pipe leading from the pressure section was in every case given a continuous upward inclination to the point of communication with the manometer reservoir, and was provided with a blow-off cock at the highest point, for the purpose of keeping this connecting pipe free from air. In the case of Manometer No. 1, this pipe was necessarily of considerable length, but the water in it could be completely changed by opening the blow-off for a few seconds. The vitiation of the results by air would require a sufficient accumulation to completely fill the cross-section of the pipe. It is reasonably certain that no such accumulation occurred in any piezometer. There was, in fact, no indication at any time that any important amount of air was carried by the water.

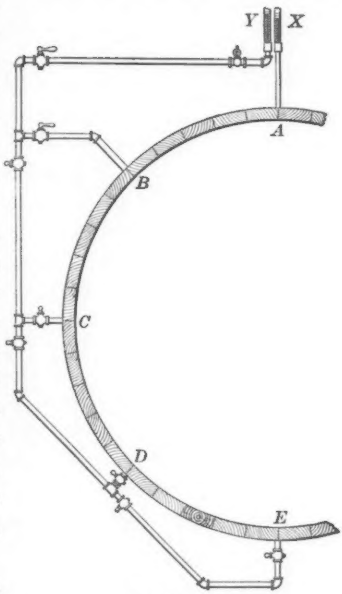


FIG. 2.

The attachment of piezometers to the main pipe was made in the same way as in the former series of observations,† except in the case of the water piezometer at Station No. 6. At this section the pipe was tapped at five points, A, B, C, D, E (Fig. 2). Two vertical glass tubes

* This value is believed to be reliable to within one-twentieth of 1 per cent. In reducing the former series of experiments, a value of 13.6 was used, the authors believing themselves to be justified in assuming, without an experimental determination, that this value was correct to the degree of accuracy demanded by the nature of the experiments. The difference between 13.57 and 13.6 would mean a difference of less than one-fourth of 1% in the values found for the loss of head. The authors have yet to learn of any experiments on flow in large pipes which can claim such a degree of accuracy as this figure represents, and do not claim such accuracy for their own experiments.

† *Transactions*, Am. Soc. C. E., Vol. xl, p. 475.

X and Y were used, the former communicating with the pipe at the single point A, the latter arranged to communicate with any one or more of the tubes running to B, C, D, E. The object of this arrangement was to test whether the indication of the piezometer was affected by the position of the point of attachment. For this purpose, simultaneous readings were taken of the water columns X and Y, the latter being in communication with the pipe at any one, or any combination, of the points B, C, D, E. The results showed a small difference between the reading of X and Y, the former being in all cases a little the higher. The oscillations of the two columns (which were somewhat rapid and not simultaneous) prevented a precise determination of the amount of this difference and of its variation with the velocity of flow. The best observations showed a difference of 0.02 ft. with a velocity of 4.7 ft. per second. No change in the reading Y appeared to be produced by changing the combination of points of communication with the pipe. It would seem, therefore, that the difference in the readings of X and Y was due to some accidental circumstance affecting the connection at A. The reading Y was used in all cases in the observations for determining loss of head in the pipe.

Measurement of Rate of Discharge.

The rate of discharge was determined as before, by attaching difference-gauges to the two Venturi meters. The two difference-gauges were placed side by side, so that both could be read by a single observer (Fig. 6, Plate V.). The connecting pipes were laid on a continuous up-grade from the pressure sections to the gauges, blow-off valves being placed at the summits to insure freedom from air.

Loss of Head in Meters.

The difference-gauges were triple, showing pressure-differences for three sections: upper section of Venturi, throat of Venturi, and full-sized section below Venturi. The pressure-difference for the first and third sections thus showed the loss of head between those points.

Programme of Tests.

In carrying out the observations, it was necessary to secure simultaneous observations of the rate of discharge and the pressure at each of the points between which the loss of head was to be computed. For this purpose, observers stationed at the several gauges in use took

FIG. 1. MANOMETER No. 1. (1899.)

FIG. 2. MANOMETER No. 2. (1899.)

FIG. 3. MANOMETER No. 3. (1899.)

FIG. 4. MANOMETER No. 5. (1899.)

FIG. 5. MANOMETER No. 6. (1899.)

FIG. 6. DIFFERENCE GAUGE. (1899.)

readings at short intervals (generally one minute or less), throughout a period previously agreed on. During each period it was aimed to maintain a uniform rate of discharge. Because of fluctuations in the consumption of power by customers, the amount of water used by the wheels could not always be kept as constant as was desired, and it was necessary in most cases to use the average of readings, which varied somewhat during the interval in question. An interval of 20 minutes was adopted as the standard period covered by an "observation," and in most cases a nearly uniform flow was maintained during four consecutive 20-minute periods. The readings obtained during each 20-minute period were averaged, giving one "observation;" and, when the variation in the flow was small during several consecutive observations, these were combined to form a "group." The amount of difference between the observations of any group may be seen by reference to Table No. 1 (Plate VI), to be explained below. At the beginning of each 20-minute interval the blow-off valves were opened for a sufficient time to insure freedom from air in the gauges and in the connecting pipes.

Reduction of Observations.

The method of reducing the observations was somewhat different from that used before;* the difference, is however, in form rather than in substance.

(1.) *Reduction of Manometer Reading to Equivalent Water Column.*—Each manometer observation was reduced to an equivalent water-piezometer reading. For this purpose a zero or datum level is assumed for each gauge, the position of which is arbitrary, but which it is convenient to take as the zero of the lower fixed scale.

The data furnished by a manometer observation are the following: Height of top of mercury column above zero of upper scale; height of mercury surface in reservoir above zero of lower scale; temperature of mercury column. Each of these quantities is found by averaging the readings taken throughout an observation period. When the pressure was very unsteady, the readings were plotted before averaging; a comparison of the plotted results obtained from the different gauges being of assistance in the selection of the exact readings to be used. In most cases the readings were sufficiently steady to make plotting unnecessary.

* *Transactions*, Am. Soc. C. E., vol. xl., p. 480.

The vertical distance between zeros of the two scales is a known constant for each gauge. Adding to this the upper reading and subtracting the lower reading, the result is the actual vertical length of the mercury column. This must be reduced to an equivalent column at a standard temperature. Strictly, this temperature should be that of the water in the portion of pipe under experiment; practically, it makes little difference what temperature is selected as the standard, except that variations in the water temperature must be taken into account, if of sufficient amount to affect the results materially. When the experiments were begun, the temperature of the water was in the neighborhood of 10° Cent., and this was chosen as the standard. The reduction to this standard temperature is made by applying the factor $1 - 0.00018\,(T - 10)$, T being the temperature of the mercury column in degrees Cent., and 0.00018 being a sufficiently exact value of the coefficient of expansion of mercury within the range of temperature found in the experiments.

The mercury column is reduced to water by multiplying by the specific gravity of mercury, which, as previously stated, was found to be 13.57. To the height of water, thus computed, must be added the lower scale reading, the zero of this scale being taken as the fixed piezometer datum.

Changes of temperature of the water in the pipe must be considered next. The difference in level of the two pressure stations on the steel pipe is about 300 ft. The difference between the pressures at these two stations will be changed appreciably by a change of even a few degrees in the temperature of the water. Thus, the coefficient of expansion of water in the neighborhood of 10° Cent. is very nearly 0.000084. A change of 4° in the temperature (say from 8° to 12°) would therefore cause the relative level of piezometers at the two points to change by about $300 \times 4 \times 0.000084 = 0.1$ ft. (very nearly). Observations of the temperature in the waste flume below the power-house showed, during the period covered by the experiments, a variation between 9.5° and 14° Cent. It is apparent, therefore, that this cause probably had an appreciable influence upon the gauge readings at Stations Nos. 1 and 2.

From observations of the temperature in the flume, an estimate was made of the mean temperature of the water in the steel pipe during each observation, and the corresponding correction was applied

1	2	3	4						5						6					7	
Group.	No.	Date and time. 1899.	Manometer No. 1. Distance between Zeros, 31.300 Ft.						Manometer No. 2. Distance between Zeros, 8.150 Ft.						Manometer No. 3. Distance between Zeros, 4.984 Ft.					Manome… Distance betwe…	
			U. Ft.	L. Ft.	Merc. Ft.	T°. Cent.	t°. Cent.	Merc. Reduc. Ft.	U. Ft.	L. Ft.	Merc. Ft.	T°. Cent.	t°. Cent.	Merc. Reduc. Ft.	U. Ft.	L. Ft.	Merc. Ft.	T°. Cent.	Merc. Reduc. Ft.	U. Ft.	L. Ft.
		June 18th.																			
"	1	12 M.- 1.00 P. M.	2.660	0.031	33.929	12.2	9.5	33.915	2.891	0.055	10.986	32.7	9.5	10.941							
A	2	3.40- 4.00 "	2.606	0.031	33.875	12.1	9.5	33.861	2.861	0.055	10.956	35.1	9.5	10.907							
A	4	4.20- 4.40 "	2.606	0.031	33.875	12.1	9.5	33.861	2.861	0.053	10.956	35.7	9.5	10.903							
B	5	4.40- 5.00 "	2.547	0.031	33.816	12.3	9.5	33.802	2.824	0.055	10.919	36.2	9.5	10.868							
B	6	5.00- 5.20 "	2.549	0.031	33.818	12.3	9.5	33.804	2.820	0.055	10.915	34.8	9.5	10.866							
B	7	5.20- 5.40 "	2.546	0.031	33.815	12.3	9.5	33.801	2.822	0.055	10.917	35.5	9.5	10.867							
B	8	5.40- 6.00 "	2.547	0.031	33.816	12.3	9.5	33.802	2.825	0.055	10.920	35.9	9.5	10.869							
B	9	6.00- 6.20 "	2.545	0.031	33.814	12.0	9.5	33.801	2.826	0.055	10.921	36.3	9.5	10.869							
		June 20th.																			
C	10	8.40- 9.00 P. M.	0.511	0.039	31.772	13.0	10.0	31.755	1.097	0.062	9.185	18.0	10.0	9.172							
C	11	9.00- 9.20 "	0.519	0.039	31.780	13.5	10.0	31.760	1.095	0.062	9.183	17.9	10.0	9.170							
C	12	9.20- 9.40 "	0.530	0.039	31.791	13.5	10.0	31.771	1.106	0.062	9.194	17.3	10.0	9.182							
C	13	9.40-10.00 "	0.574	0.039	31.835	13.5	10.0	31.815	1.143	0.062	9.231	17.0	10.0	9.219							
D	14	10.20-10.40 "	1.521	0.035	32.786	13.0	10.0	32.768	1.937	0.059	10.028	16.0	10.0	10.017							
D	15	10.40-11.00 "	1.564	0.035	32.829	13.0	10.0	32.811	1.964	0.059	10.055	16.0	10.0	10.044							
D	16	11.00-11.20 "	1.596	0.035	32.861	13.0	10.0	32.843	2.005	0.058	10.097	15.8	10.0	10.086							
D	17	11.20-11.40 "	1.643	0.035	32.908	13.0	10.0	32.890	2.032	0.058	10.124	16.0	10.0	10.113							
		June 22d.																			
E	18	6.00- 6.20 P. M.	2.214	0.033	33.481	10.8	11.5	33.490	2.535	0.056	10.629	24.1	11.5	10.603							
E	19	6.20- 6.40 "	2.228	0.033	33.495	10.3	11.5	33.497	2.542	0.056	10.636	22.8	11.5	10.613							
E	20	6.40- 7.00 "	2.226	0.033	33.493	10.0	11.5	33.497	2.542	0.056	10.636	23.3	11.5	10.612							
E	21	7.00- 7.20 "	2.185	0.033	33.452	9.9	11.5	33.457	2.513	0.057	10.606	23.0	11.5	10.582							
F	22	8.40- 9.00 "	0.153	0.041	31.412	11.5	12.5	31.410	0.808	0.063	8.889	16.7	12.5	8.880							
F	23	9.00- 9.20 "	0.167	0.041	31.426	11.9	12.5	31.421	0.820	0.063	8.907	16.1	12.5	8.899							
F	24	9.20- 9.40 "	0.189	0.041	31.448	12.1	12.5	31.442	0.825	0.063	8.912	16.5	12.5	8.904							
F	25	9.40-10.00 "	0.241	0.041	31.500	12.3	12.5	31.494	0.864	0.063	8.951	16.3	12.5	8.943							
		June 24th.																			
G	26	6.20- 6.40 P. M.	1.996	0.034	33.262	19.0	12.5	33.215	2.327	0.057	10.420	29.5	12.5	10.385							
G	27	6.40- 7.00 "	1.961	0.034	33.227	12.3	12.5	33.221	2.320	0.057	10.413	28.6	12.5	10.380							
G	28	7.00- 7.20 "	1.960	0.034	33.226	12.1	12.5	33.220	2.325	0.057	10.418	28.4	12.5	10.385							
G	29	7.20- 7.40 "	1.945	0.034	33.211	12.0	12.5	33.206	2.306	0.057	10.399	26.3	12.5	10.370							
"	30	8.40- 9.00 "	0.557	0.039	31.818	14.5	13.0	31.800	1.177	0.062	9.265	26.7	13.0	9.237							
H	31	9.00- 9.20 "	0.153	0.041	31.412	16.0	13.0	31.386	0.808	0.065	8.890	26.7	13.0	8.863							
H	32	9.20- 9.40 "	0.160	0.041	31.419	14.5	13.0	31.409	0.821	0.063	8.908	27.3	13.0	8.882							
H	33	9.40-10.00 "	0.202	0.041	31.461	14.8	13.0	31.442	0.850	0.063	8.937	27.0	13.0	8.912							
		June 25th.																			
"	34	12 M.- 1.00 P. M.	2.637	0.031	33.906	14.0	13.5	33.891	2.842	0.055	10.937	23.7	13.5	10.913	2.483	0.005	7.462	26.1	7.440	1.317	0.007
		June 26th.																			
"	35	4.00- 4.20 P. M.													2.178	0.006	7.156	26.5	7.135	1.064	0.008
I	36	4.20- 4.40 "													2.171	0.006	7.149	26.7	7.127	1.059	0.008
I	37	4.40- 5.00 "													2.174	0.006	7.152	27.2	7.130	1.046	0.008
I	38	5.00- 5.20 "													2.185	0.006	7.163	27.6	7.140	1.052	0.008
I	39	6.40- 7.00 "																			
		June 27th.																			
J	40	3.00- 3.20 P. M.													2.478	0.005	7.457	28.8	7.432	1.319	0.007
J	41	3.20- 3.40 "													2.477	0.005	7.456	29.5	7.430	1.319	0.007
J	42	3.40- 4.00 "													2.477	0.005	7.456	29.6	7.430	1.319	0.007
J	43	4.00- 4.20 "													2.475	0.005	7.454	28.7	7.429	1.318	0.007
K	44	4.40- 5.00 "													1.654	0.008	6.630	29.7	6.607	0.571	0.010
K	45	5.00- 5.20 "													1.643	0.008	6.619	29.5	6.596	0.568	0.010
K	46	5.20- 5.40 "													1.643	0.008	6.619	29.4	6.598	0.564	0.010
K	47	5.40- 6.00 "													1.643	0.008	6.619	28.7	6.597	0.564	0.010
		June 28th.																			
L	48	3.00- 3.20 P. M.													2.187	0.006	7.165	32.8	7.136	1.055	0.008
L	49	3.20- 3.40 "													2.189	0.006	7.167	32.5	7.138	1.060	0.008
L	50	3.40- 4.00 "													2.181	0.006	7.159	32.9	7.130	1.063	0.008
L	51	4.00- 4.20 "													2.170	0.006	7.148	32.9	7.119	1.056	0.008
M	52	4.40- 5.00 "													1.591	0.008	6.567	33.0	6.540	0.518	0.010
M	53	5.00- 5.20 "													1.583	0.008	6.559	32.6	6.532	0.510	0.010
M	54	5.20- 5.40 "													1.581	0.008	6.557	33.0	6.531	0.507	0.010
M	55	5.40- 6.00 "													1.397	0.008	6.373	32.4	6.347	0.380	0.010
		June 29th.																			
N	56	3.00- 3.20 P. M.													2.460	0.005	7.439	34.1	7.407	1.300	0.007
N	57	3.20- 3.40 "													2.461	0.005	7.440	33.9	7.408	1.300	0.007
N	58	3.40- 4.00 "													2.459	0.005	7.438	33.0	7.407	1.300	0.007
N	59	4.00- 4.20 "													2.459	0.005	7.438	34.0	7.406	1.300	0.007
P	60	5.00- 5.20 "																			
P	61	5.20- 5.40 "																			
P	62	5.40- 6.00 "																			
"	63	6.00- 6.20 "																			
		June 30th.																			
O	64	6.00- 6.20 P. M.																			
O	65	6.20- 6.40 "																			
O	66	6.40- 7.00 "																			
"	67	7.00- 7.20 "																			
R	68	8.40- 9.00 "	0.504	0.041	31.763	17.0	12.0	31.728													
R	69	9.00- 9.20 "	0.504	0.041	31.763	17.4	12.0	31.726													
R	70	9.20- 9.40 "	0.523	0.041	31.782	17.5	12.0	31.744													
R	71	9.40-10.00 "	0.541	0.041	31.800	16.9	12.0	31.766													
		July 1st.																			
S.	72	8.40- 9.00 P. M.	—0.425	0.043	30.832	22.0	13.0	30.772	0.296	0.065	8.381	23.5	13.0	8.363							
S	73	9.00- 9.20 "	—0.400	0.043	30.857	22.0	13.0	30.797	0.320	0.065	8.405	21.5	13.0	8.387							
S	74	9.20- 9.40 "	—0.331	0.043	30.926	17.0	13.0	30.894	0.400	0.065	8.485	23.5	13.0	8.467							
S	75	9.40-10.00 "	—0.294	0.043	30.963	17.5	13.0	30.923	0.426	0.065	8.511	23.0	13.0	8.493							
		July 2d.																			
"	76	12 M.- 1.00 P. M.	2.657	0.036	33.921	14.0	13.5	33.906	2.869	0.055	10.964	27.0	13.5	10.933							
T	77	8.40- 8.50 "													0.479	0.013	5.450	23.0	5.437	—0.486	0.014
T	78	8.50- 9.00 "													0.494	0.013	5.465	23.5	5.452	—0.470	0.014
T	79	9.20- 9.40 "													0.476	0.013	5.447	23.0	5.434	—0.484	0.014
T	80	9.40-10.00 "													0.481	0.013	5.452	22.5	5.440	—0.480	0.014
		July 5th.																			
U	81	8.40- 9.00 P. M.																			
U	82	9.00- 9.20 "																			
U	83	9.20- 9.40 "																			
U	84	9.40-10.00 "																			

TABLE No. 1.

7					8					9							10	
Manometer No. 4. Distance between Zeros, 2.104 Ft.					Manometer No. 5. Distance between Zeros, 2.752 Ft.					Equivalent Water Piezometer.							Difference of … Column…	
U. Ft.	L. Ft.	Merc. Ft.	T°. Cent.	Merc. Reduc. Ft.	U. Ft.	L. Ft.	Merc. Ft.	T° Cent.	Merc. Reduc. Ft.	1 [+407.10] Ft.	2 [+108.56] Ft.	3 Ft.	4 Ft.	5 Ft	6 Ft.	7 Ft.	1-2 [+298.54] Ft.	3-4 Ft.
......	......	......	......	......	......	......	......	......	......	53.16	39.97	......	......	......	......	......	13.19	......
......	......	......	......	......	......	......	......	......	......	52.42	39.50	......	......	......	......	......	12.92	......
......	......	......	......	......	......	......	......	......	......	52.42	39.49	......	......	......	......	......	12.93	......
......	......	......	......	......	......	......	......	......	......	51.62	38.97	......	......	......	......	......	12.65	......
......	......	......	......	......	......	......	......	......	......	51.65	38.95	......	......	......	......	......	12.70	......
......	......	......	......	......	......	......	......	......	......	51.61	38.96	......	......	......	......	......	12.65	......
......	......	......	......	......	......	......	......	......	......	51.63	38.99	......	......	......	......	......	12.64	......
......	......	......	......	......	......	......	......	......	......	51.61	38.99	......	......	......	......	......	12.62	......
......	......	......	......	......	......	......	......	......	......	23.86	15.97	......	......	......	......	......	7.89	......
......	......	......	......	......	......	......	......	......	......	23.92	15.94	......	......	......	......	......	7.98	......
......	......	......	......	......	......	......	......	......	......	24.07	16.10	......	......	......	......	......	7.97	......
......	......	......	......	......	......	......	......	......	......	24.67	16.61	......	......	......	......	......	8.06	......
......	......	......	......	......	......	......	......	......	......	37.60	27.43	......	......	......	......	......	10.17	......
......	......	......	......	......	......	......	......	......	......	38.18	27.80	......	......	......	......	......	10.34	......
......	......	......	......	......	......	......	......	......	......	38.61	28.36	......	......	......	......	......	10.25	......
......	......	......	......	......	......	......	......	......	......	39.25	28.73	......	......	......	......	......	10.52	......
......	......	......	......	......	......	......	......	......	......	47.26	35.38	......	......	......	......	......	11.88	......
......	......	......	......	......	......	......	......	......	......	47.49	35.52	......	......	......	......	......	11.97	......
......	......	......	......	......	......	......	......	......	......	47.49	35.50	......	......	......	......	......	11.99	......
......	......	......	......	......	......	......	......	......	......	46.94	35.09	......	......	......	......	......	11.85	......
......	......	......	......	......	......	......	......	......	......	19.17	12.00	......	......	......	......	......	7.17	......
......	......	......	......	......	......	......	......	......	......	19.32	12.26	......	......	......	......	......	7.06	......
......	......	......	......	......	......	......	......	......	......	19.61	12.33	......	......	......	......	......	7.28	......
......	......	......	......	......	......	......	......	......	......	20.32	12.86	......	......	......	......	......	7.46	......
......	......	......	......	......	......	......	......	......	......	43.66	32.42	......	......	......	......	......	11.24	......
......	......	......	......	......	......	......	......	......	......	43.74	32.35	......	......	......	......	......	11.39	......
......	......	......	......	......	......	......	......	......	......	43.73	32.42	......	......	......	......	......	11.31	......
......	......	......	......	......	......	......	......	......	......	43.54	32.22	......	......	......	......	......	11.32	......
......	......	......	......	......	......	......	......	......	......	24.47	16.85	......	......	......	......	−2.05	7.62	......
......	......	......	......	......	......	......	......	......	......	18.85	11.80	......	......	......	......	−2.11	7.05	......
......	......	......	......	......	......	......	......	......	......	19.06	12.03	......	......	......	......	−2.17	7.03	......
......	......	......	......	......	......	......	......	......	......	19.61	12.44	......	......	......	......	−2.20	7.17	......
1.317	0.007	3.414	23.5	3.406	1.025	0.020	3.757	25.0	3.746	52.83	39.58	100.97	46.23	50.85	1.36	−3.27	13.25	54.74
1.064	0.008	3.160	24.9	3.152	......	......	......	......	......	......	......	96.82	42.78	......	2.67	−1.58	......	54.04
1.059	0.008	3.155	25.2	3.146	0.771	0.021	3.502	23.0	3.494	......	......	96.72	42.70	47.43	2.67	−1.58	......	54.02
1.046	0.008	3.142	25.4	3.133	0.759	0.021	3.490	23.0	3.482	......	......	96.76	42.52	47.27	2.66	−1.59	......	54.24
1.052	0.[illegible]	3.148	25.1	3.139	0.765	0.021	3.499	23.0	3.491	......	......	96.89	42.60	47.39	2.66	−1.60	......	54.29
......	......	......	......	......	−0.024	0.024	2.704	23.0	2.696	......	......	......	......	36.64	1.72	−1.72	......	......
1.319	0.007	3.416	29.6	3.404	1.036	0.020	3.768	29.0	3.755	......	......	100.86	46.20	50.98	2.96	−1.56	......	54.66
1.319	0.007	3.416	29.3	3.404	1.034	0.020	3.766	28.8	3.753	......	......	100.84	46.20	50.93	2.95	−1.58	......	54.63
1.319	0.007	3.416	29.4	3.404	1.036	0.020	3.770	27.7	3.758	......	......	100.83	46.20	51.02	2.95	−1.60	......	54.63
1.318	0.007	3.415	29.4	3.403	1.030	0.020	3.762	27.0	3.750	......	......	100.82	46.19	50.91	2.94	−1.61	......	51.61
0.571	0.010	2.665	29.4	2.656	0.294	0.023	3.023	27.0	3.014	......	......	89.66	36.05	40.92	2.10	−1.66	......	53.61
0.566	0.010	2.660	28.8	2.651	0.286	0.023	3.015	26.5	3.006	......	......	89.51	35.96	40.81	2.07	−1.68	......	53.53
0.564	0.010	2.658	28.9	2.649	0.286	0.023	3.015	26.5	3.006	......	......	89.52	35.96	40.81	2.04	−1.71	......	51.56
0.564	0.010	2.638	27.2	2.650	0.285	0.023	3.314	26.3	3.005	......	......	89.53	35.97	40.80	2.08	−1.74	......	53.56
1.035	0.008	3.151	33.0	3.138	0.771	0.021	3.502	32.2	3.488	......	......	96.84	42.59	47.35	2.50	−1.76	......	54.25
1.060	0.008	3.156	32.6	3.143	0.773	0.021	3.504	31.7	3.490	......	......	96.87	42.66	47.38	2.50	−1.77	......	54.21
1.063	0.008	3.159	33.0	3.146	0.774	0.021	3.505	30.8	3.492	......	......	96.76	42.70	47.41	2.52	−1.78	......	54.06
1.056	0.008	3.152	32.9	3.139	0.768	0.021	3.495	30.5	3.486	......	......	96.61	42.60	47.33	2.51	−1.79	......	54.01
0.518	0.010	2.612	32.3	2.602	0.239	0.023	2.968	30.3	2.937	......	......	88.76	35.32	40.15	1.90	−1.81	......	53.44
0.510	0.010	2.604	31.9	2.594	0.232	0.023	2.961	30.0	2.950	......	......	88.63	35.21	40.05	1.87	−1.82	......	53.44
0.507	0.010	2.601	30.1	2.592	0.228	0.023	2.957	29.5	2.947	......	......	88.63	35.18	40.01	1.86	−1.83	......	53.45
0.520	0.010	2.611	28.5	2.605	0.241	0.023	2.970	29.0	2.960	......	......	88.85	35.36	40.19	1.86	−1.84	......	53.49
1.300	0.007	3.397	31.1	3.384	1.016	0.020	3.743	32.6	3.733	......	......	100.58	45.98	50.68	2.81	−1.71	......	54.59
1.300	0.007	3.397	31.4	3.384	1.015	0.020	3.747	31.7	3.732	......	......	100.53	45.98	50.66	2.80	−1.72	......	54.60
1.300	0.007	3.397	31.5	3.384	1.012	0.020	3.744	31.0	3.730	......	......	100.52	45.98	50.64	2.80	−1.72	......	51.59
1.300	0.007	3.397	31.5	3.384	1.010	0.020	3.742	31.4	3.727	......	......	100.51	45.98	50.60	2.80	−1.73	......	54.58
......	......	......	......	......	0.130	0.023	2.859	30.2	2.849	......	......	......	......	38.68	1.79	−1.79	......	......
......	......	......	......	......	0.128	0.023	2.857	30.0	2.847	......	......	......	......	38.66	1.76	−1.81	......	......
......	......	......	......	......	0.129	0.021	2.858	29.8	2.848	......	......	......	......	34.67	1.75	−1.83	......	......
......	......	......	......	......	0.152	0.023	2.881	29.4	2.871	......	......	......	......	38.16	1.75	−1.86	......	......
......	......	......	......	......	0.446	0.022	3.176	25.6	3.167	......	......	......	......	43.00	2.04	......	......	......
......	......	......	......	......	0.445	0.022	3.175	26.1	3.166	......	......	......	......	42.98	2.02	......	......	......
......	......	......	......	......	0.442	0.022	3.172	25.9	3.163	......	......	......	......	42.94	2.00	......	......	......
......	......	......	......	......	0.409	0.022	3.13[illegible]	25.9	3.130	......	......	......	......	42.50	1.95	......	......	......
......	......	......	......	......	−0.499	0.024	2.229	25.0	2.223	23.49	......	......	......	30.19	0.96	−1.96	......	......
......	......	......	......	......	−0.496	0.024	2.232	24.5	2.226	23.46	......	......	......	30.23	0.94	−1.95	......	......
......	......	......	......	......	−0.487	0.004	2.241	24.5	2.235	23.71	......	......	......	30.35	0.96	−1.95	......	......
......	......	......	......	......	−0.470	0.004	2.258	21.5	2.252	24.00	......	......	......	30.56	0.94	−1.95	......	......
......	......	......	......	......	−1.192	0.026	1.534	24.0	1.530	10.52	4.99	......	......	20.79	0.23	−1.99	5.53	......
......	......	......	......	......	−1.167	0.026	1.559	24.0	1.555	10.86	5.32	......	......	21.13	0.20	−1.99	5.54	......
......	......	......	......	......	−1.101	0.026	1.625	23.5	1.621	12.17	6.40	......	......	22.02	0.24	−2.00	5.77	......
......	......	......	......	......	−1.089	0.026	1.637	23.0	1.653	12.64	6.76	......	......	22.40	0.25	−2.00	5.88	......
					1.049	0.021	3.780	30.9	3.766	53.04	39.86			51.12	1.57	−3.07	13.18	
−0.486	0.014	1.604	22.0	1.601	−0.747	0.025	1.980	22.5	1.976	......	......	73.79	21.74	26.84	0.65	−1.99	......	52.05
−0.470	0.014	1.620	22.0	1.617	−0.736	0.025	1.991	22.5	1.987	......	......	74.00	21.96	26.99	0.66	−1.99	......	52.04
−0.484	0.014	1.606	22.0	1.603	−0.754	0.025	1.973	21.5	1.969	......	......	74.76	21.77	26.74	0.58	−2.00	......	51.99
−0.480	0.014	1.610	22.0	1.607	−0.750	0.025	1.977	21.5	1.973	......	......	73.83	21.69	26.80	0.56	−2.00	......	52.01
......	......	......	......	......	−0.624	0.025	2.103	22.0	2.098	......	......	......	......	28.49	0.70	−2.02	......	......
......	......	......	......	......	−0.635	0.025	2.092	21.3	2.086	......	......	......	......	28.36	0.66	−2.02	......	......
......	......	......	......	......	−0.634	0.025	2.093	20.5	2.089	......	......	......	......	28.27	0.63	−2.02	......	......
......	......	......	......	......	−0.625	0.025	2.102	20.5	2.096	......	......	......	......	28.49	0.68	−2.03	......	......

10			11							12		13		14	15		16	17
[DIFF]ERENCE OF PIEZOMETER COLUMNS.			LOSS OF HEAD.							SOUTH METER.		NORTH METER.		Total rate of discharge.	MEAN VELOCITY IN FEET PER SECOND.		No.	Gauge.
			1-3		3-4		5-6											
3-4 Ft.	4-5 Ft.	5-6 Ft.	Total length 4 427 Ft.	Per 1 000 ft. Ft.	Total length 2 710 Ft.	Per 1 000 ft. Ft.	Total length 22 672 Ft.	Per 1 000 ft. Ft.	4-5 Ft.	Gauge. Ft.	Rate of discharge. Cu. ft. per second.	Gauge. Ft.	Rate of discharge. Cu. ft. per second.	Cu. ft. per second.	Steel Pipe.	Wood Pipe.		
......	......	......	−0.004	−0.0009	......	......	......	......	......	......	......	......	......	......	......	......	1	..
......	......	......	0.27	0.060	......	......	......	......	......	0.038	19.60	......	......	19.60	0.689	......	2	A.
......	......	......	0.25	0.057	......	......	......	......	......	0.038	19.60	......	......	19.60	0.689	......	4	A.
......	......	......	0.54	0.121	......	......	......	......	44 ft. of wood pipe east of tunnel, + 108.7 ft. of tunnel + 93 ft. of wood pipe west of tunnel.	0.101	31.86	......	......	31.86	1.120	......	5	B.
......	......	......	0.48	0.109	......	......	......	......		0.101	31.86	......	......	31.86	1.120	......	6	B.
......	......	......	0.54	0.121	......	......	......	......		0.101	31.86	......	......	31.86	1.120	......	7	B.
......	......	......	0.55	0.124	......	......	......	......		0.101	31.86	......	......	31.86	1.120	......	8	B.
......	......	......	0.56	0.127	......	......	......	......		0.101	31.86	......	......	31.86	1.120	......	9	B.
......	......	......	5.30	1.197	......	......	......	......		0.659	80.40	0.186	43.10	123.50	4.341	......	10	C.
......	......	......	5.21	1.176	......	......	......	......		0.668	80.91	0.184	42.87	123.81	4.352	......	11	C.
......	......	......	5.22	1.179	......	......	......	......		0.660	80.46	0.187	43.21	123.67	4.347	......	12	C.
......	......	......	5.12	1.157	......	......	......	......		0.648	79.74	0.186	43.10	122.84	4.318	......	13	C.
......	......	......	3.02	0.682	......	......	......	......		0.582	75.63	0.027	16.53	92.16	3.240	......	14	D.
......	......	......	2.80	0.633	......	......	......	......		0.556	73.94	0.027	16.53	90.47	3.180	......	15	D.
......	......	......	2.94	0.664	......	......	......	......		0.537	72.69	0.027	16.53	89.22	3.136	......	16	D.
......	......	......	2.67	0.602	......	......	......	......		0.510	70.88	0.027	16.53	87.41	3.073	......	17	D.
......	......	......	1.31	0.296	......	......	......	......		0.345	58.46	......	......	58.46	2.055	......	18	E.
......	......	......	1.22	0.274	......	......	......	......		0.331	57.27	......	......	57.27	2.013	......	19	E.
......	......	......	1.20	0.271	......	......	......	......		0.331	57.27	......	......	57.27	2.013	......	20	E.
......	......	......	1.31	0.302	......	......	......	......		0.359	59.53	......	......	59.53	2.093	......	21	E.
......	......	......	6.02	1.359	......	......	......	......		0.816	89.29	0.206	45.33	134.62	4.732	......	22	F.
......	......	......	6.13	1.384	......	......	......	......		0.815	89.23	0.206	45.33	134.56	4.730	......	23	F.
......	......	......	5.91	1.335	......	......	......	......		0.812	89.08	0.203	45.00	134.08	4.713	......	24	F.
......	......	......	5.73	1.295	......	......	......	......		0.793	88.04	0.203	45.00	133.04	4.677	......	25	F.
......	......	......	1.95	0.440	......	......	......	......		0.544	73.16	......	......	73.16	2.572	......	26	G.
......	......	......	1.80	0.406	......	......	......	......		0.544	73.16	......	......	73.16	2.572	......	27	G.
......	......	......	1.88	0.425	......	......	......	......		0.546	73.29	......	......	73.29	2.576	......	28	G.
......	......	......	1.87	0.421	......	......	......	......		0.551	73.62	......	......	73.62	2.588	......	29	G.
......	......	......	5.57	1.258	......	......	......	......	......	0.416	64.10	0.368	60.35	124.45	4.375	......	30	..
......	......	......	6.14	1.387	......	......	......	......	......	0.508	70.60	0.439	65.83	136.43	4.796	......	31	H.
......	......	......	6.15	1.390	......	......	......	......	......	0.504	70.46	0.436	65.61	136.07	4.783	......	32	H.
......	......	......	6.08	1.350	......	......	......	......	......	0.499	70.12	0.431	65.24	135.36	4.758	......	33	H.
54.74	−4.62	49.49	−0.060	−0.0135	0.00	0.000	+0.080	+0.0013	0.00	0.000	0.00	0.000	0.00	0.00	0.000	......	34	..
54.04	......	......	......	......	0.70	0.258	......	......	......	0.022	14.93	0.219	46.72	61.65	......	2.150	35	I.
54.02	−4.73	44.76	......	......	0.73	0.266	4.76	0.210	0.11	0.020	14.24	0.223	47.14	61.38	......	2.141	36	I.
54.24	−4.75	44.61	......	......	0.50	0.184	4.91	0.217	0.13	0.019	13.88	0.240	47.86	61.74	......	2.154	37	I.
54.29	−4.79	41.73	......	......	0.45	0.166	4.79	0.211	0.17	0.019	13.88	0.224	47.24	61.12	......	2.132	38	I.
......	......	34.92	......	......	......	......	14.60	0.644	......	0.387	61.86	0.209	45.65	107.51	......	3.750	39	..
54.66	−4.78	48.02	......	......	0.08	0.029	1.50	0.066	0.16	......	......	0.112	33.53	33.53	......	1.170	40	J.
54.63	−4.75	48.00	......	......	0.11	0.041	1.52	0.067	0.13	......	......	0.113	33.64	33.68	......	1.175	41	J.
54.63	−4.82	48.07	......	......	0.11	0.041	1.45	0.064	0.20	......	......	0.113	33.68	33.68	......	1.175	42	J.
51.61	−4.72	47.97	......	......	0.11	0.041	1.55	0.068	0.10	......	......	0.114	33.83	33.83	......	1.180	43	J.
53.61	−4.87	38.82	......	......	1.13	0.417	10.70	0.472	0.25	0.359	59.04	0.114	33.83	92.87	......	3.239	44	K.
53.53	−4.38	33.74	......	......	1.21	0.446	10.78	0.475	0.21	0.354	59.20	0.113	33.68	92.88	......	3.240	45	K.
51.56	−4.85	38.77	......	......	1.18	0.435	10.75	0.474	0.23	0.355	59.29	0.112	33.53	92.82	......	3.238	46	K.
53.56	−4.85	38.78	......	......	1.18	0.435	10.74	0.474	0.21	0.355	59.29	0.112	33.53	92.82	......	3.238	47	K.
54.25	−4.78	44.85	......	......	0.49	0.181	4.67	0.206	0.14	0.018	13.51	0.227	47.55	61.06	......	2.130	48	L.
54.21	−4.73	44.88	......	......	0.53	0.196	4.64	0.205	0.10	0.021	14.59	0.224	47.24	61.84	......	2.157	49	L.
54.06	−4.71	44.29	......	......	0.63	0.231	4.63	0.204	0.09	0.018	13.51	0.219	46.72	60.23	......	2.101	50	L.
54.01	−4.78	44.88	......	......	0.73	0.269	4.70	0.207	0.11	0.019	13.88	0.220	46.83	60.71	......	2.118	51	L.
53.44	−4.83	38.25	......	......	1.30	0.480	11.27	0.497	0.21	0.229	47.76	0.225	47.35	95.11	......	3.318	52	M.
53.44	−4.84	38.18	......	......	1.30	0.480	11.31	0.500	0.23	0.231	47.97	0.227	47.86	95.83	......	3.343	53	M.
53.45	−4.83	38.15	......	......	1.29	0.476	11.37	0.501	0.21	0.230	47.86	0.227	47.55	95.41	......	3.328	54	M.
53.49	−4.83	38.33	......	......	1.25	0.461	11.19	0.494	0.21	0.232	48.07	0.219	46.72	94.79	......	3.306	55	M.
54.59	−4.75	47.87	......	......	0.14	0.058	1.65	0.073	0.13	......	......	0.127	35.69	35.69	......	1.245	56	N.
54.60	−4.73	47.88	......	......	0.13	0.048	1.66	0.073	0.11	......	......	0.127	35.69	35.69	......	1.245	57	N.
51.59	−4.71	47.84	......	......	0.15	0.035	1.69	0.074	0.09	......	......	0.126	35.55	35.55	......	1.240	58	N.
54.58	−4.67	47.80	......	......	0.16	0.039	1.72	0.076	0.06	......	......	0.127	35.69	35.69	......	1.245	59	N.
......	......	34.89	......	......	......	......	12.63	0.537	......	0.331	57.27	0.191	43.67	100.94	......	3.521	60	P.
......	......	36.90	......	......	......	......	12.68	0.557	......	0.332	57.36	0.193	43.89	101.25	......	3.533	61	P.
......	......	36.98	......	......	......	......	12.40	0.556	......	0.333	57.44	0.191	43.67	101.11	......	3.527	62	P.
......	......	37.23	......	......	......	......	12.20	0.542	......	0.330	57.19	0.180	42.41	99.60	......	3.474	63	
......	......	40.96	......	......	......	......	8.56	0.378	......	0.170	41.23	0.179	42.29	83.52	......	2.913	64	Q.
......	......	40.96	......	......	......	......	8.56	0.374	......	0.170	41.23	0.182	42.64	83.87	......	2.925	65	Q.
......	......	40.94	......	......	......	......	8.58	0.378	......	0.171	41.35	0.180	42.41	83.76	......	2.922	66	Q.
......	......	40.55	......	......	......	......	8.97	0.396	......	0.183	42.76	0.184	42.87	85.63	......	2.987	67	
......	......	29.23	......	......	......	......	20.29	0.893	......	0.490	69.49	0.335	57.61	127.10	4.468	4.433	68	R.
......	......	29.29	......	......	......	......	20.33	0.897	......	0.491	69.56	0.342	58.21	127.77	4.491	4.457	69	R.
......	......	29.42	......	......	......	......	20.10	0.887	......	0.487	69.28	0.341	58.12	127.40	4.478	4.444	70	R.
......	......	29.64	......	......	......	......	19.88	0.877	......	0.484	69.07	0.336	57.70	126.77	4.456	4.422	71	R.
......	......	30.56	7.66	1.730	......	......	28.96	1.277	......	0.863	91.77	0.377	61.07	152.84	5.373	5.331	72	S.
......	......	30.93	7.65	1.727	......	......	28.59	1.261	......	0.857	91.46	0.376	60.99	152.45	5.359	5.317	73	S.
......	......	21.78	7.41	1.675	......	......	27.74	1.246	......	0.818	89.39	0.377	61.07	150.46	5.289	5.248	74	S.
......	......	22.21	7.31	1.651	......	......	27.31	1.205	......	0.804	88.64	0.376	60.99	149.63	5.200	5.219	75	S.
......	......	49.55	+0.004	+0.0009	......	......	−0.030	−0.0013	......	0.000	0.00	0.000	0.0	0.00	0.000	0.000	76	..
52.05	−5.10	26.19	......	......	2.69	0.998	23.33	1.029	0.48	0.848	90.99	0.229	47.76	138.75	......	4.840	77	T.
52.04	−5.03	26.33	......	......	2.70	0.996	23.19	1.023	0.42	0.842	90.67	0.229	47.76	138.43	......	4.829	78	T.
51.99	−4.97	26.16	......	......	2.75	1.015	23.36	1.030	0.35	0.850	91.09	0.234	48.27	139.36	......	4.861	79	T.
52.01	−4.98	26.34	......	......	2.73	1.007	23.28	1.027	0.36	0.844	90.78	0.234	48.27	139.05	......	4.850	80	T.
......	......	27.79	......	......	......	......	21.73	0.958	......	0.683	81.83	0.279	52.65	134.48	......	4.691	81	U.
......	......	27.70	......	......	......	......	21.82	0.963	......	0.686	81.91	0.280	52.74	134.65	......	4.698	82	U.
......	......	27.74	......	......	......	......	21.78	0.961	......	0.685	81.94	0.283	53.02	134.96	......	4.707	83	U.
......	......	27.87	......	......	......	......	21.65	0.955	......	0.682	81.71	0.277	52.46	134.17	......	4.680	84	U.

to the reduced water column. Thus, if the water temperature is t° Cent., the piezometer column, at 10°, computed as above, is multiplied by the factor $1 + 0.000084\ (t - 10)$.

This correction was applied only in case of Manometers Nos. 1 and 2. In the case of the wood pipe it is of comparatively little importance, because of the much smaller slope of the pipe. Moreover, although the flume temperature may give a fairly reliable indication of the variations of temperature in the steel pipe, it would be hopeless to attempt to secure any reliable estimate of the changes of temperature in the long section of wood pipe.

(*2.*) *Computation of Loss of Head.*—The loss of head between any two stations, due to a given velocity of flow, may be found by determining the difference between the piezometer columns at the two stations, and comparing it with the like difference under static conditions.* Thus, if z denotes the difference between simultaneous values of the piezometer heights at the two stations, and Z is the value of z under static conditions, $Z - z$ is the loss of head between the two stations. The datum of reference must remain constant for each piezometer, but its actual position is arbitrary. If the two sections of pipe have unequal diameters, the velocity-head must be added to the piezometer height in every case; but, with a uniform pipe, the velocity terms disappear from the value of the loss of head.

(*3.*) *Computation of Rate of Discharge.*—From a difference-gauge observation, the rate of discharge is computed in the usual way. The velocity through the throat of the Venturi is given by the formula $v = k' \sqrt{2\, g\, H}$, in which H is "head on Venturi," and the coefficient k' is the product of the friction coefficient k (in the notation of the previous paper), and the coefficient depending upon the areas of the upper section and throat of the Venturi. The values of k' for the Ogden meters, as furnished by the manufacturers were given in the former paper.†

General Results.

From each observation-group, the values of the following quantities have been computed: Loss of head per thousand feet; coefficient c in the Chezy formula $v = c \sqrt{r\, s}$; and "coefficient of roughness"

* In the previous paper (*Transactions*, Am. Soc. C. E., Vol. xl, p. 481), the method used was substantially the same; but the loss of head was first computed in mercury and then reduced to water, while in the present case each separate manometer observation was reduced to an equivalent water piezometer reading. This method was adopted for the reason that one of the gauges was a water piezometer, and its readings required no reduction.

† *Transactions*, Am. Soc. C. E., Vol. xl, p. 482.

n in Kutter's formula. These have been tabulated, and the values of c, n and loss of head per thousand feet are also shown graphically, being plotted with mean velocity of flow v as abscissas. Mean curves are drawn, representing each of these quantities as a function of the velocity, and, from the mean curves, generalized tables are computed. In these tables are included values of the friction coefficient f in the formula

$$H' = f \frac{l}{d} \frac{v^2}{2g},$$

H' being total loss of head in length l of pipe. These values are computed from those of c, from the relation

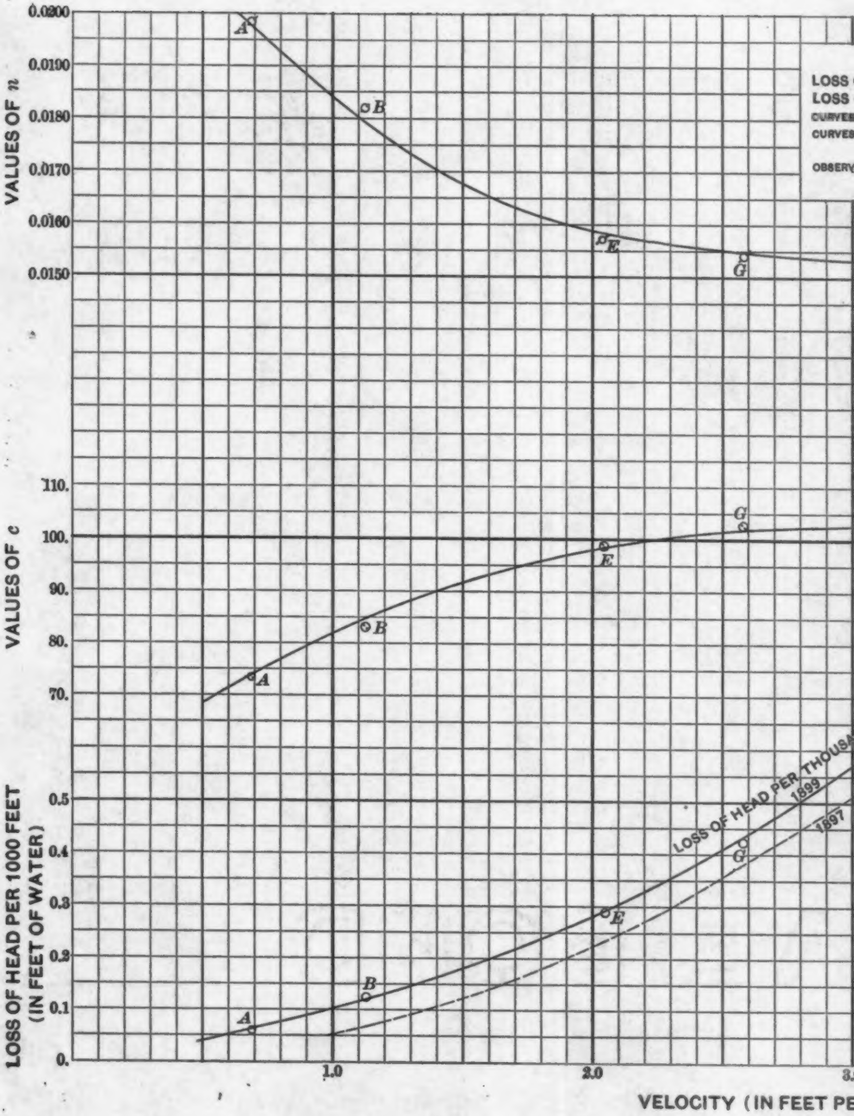
$$f = \frac{8g}{c^2}.$$

II.—Results of the Experiments.

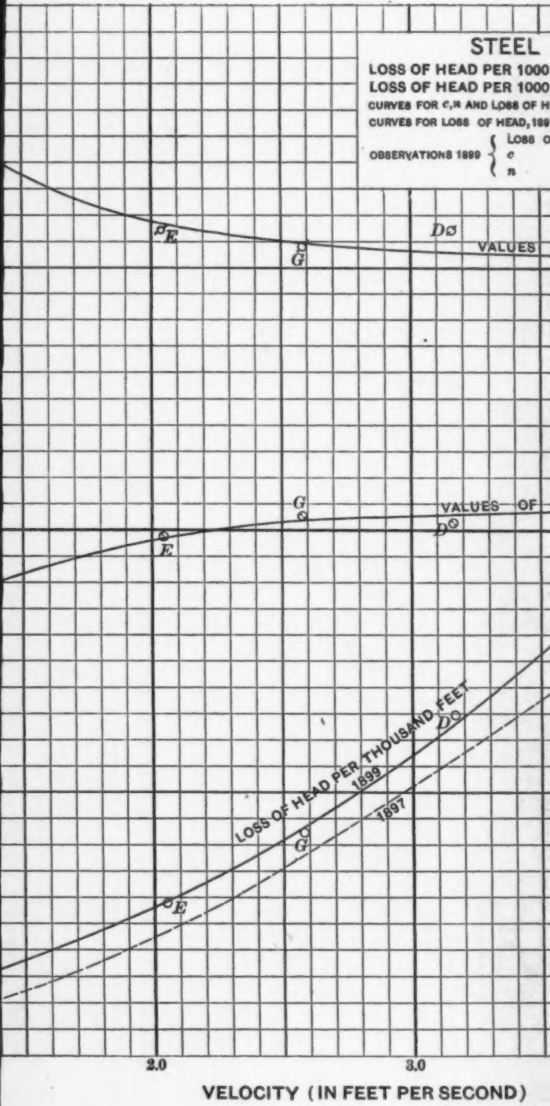
Record of Observations.

The experimental data for the entire series of observations are shown in Table No. 1 (Plate VI). The observations are numbered in chronological order, the numbers being given in Column 2 of the table. The total number is 84; but No. 3 was rejected because it showed so great a discrepancy when compared with Nos. 2 and 4, in which the rate of discharge had the same value as in No. 3. In nearly every case the period of an observation was 20 minutes, though the actual interval during which readings were taken was less than this by from 2 to 5 minutes, because of the time occupied in opening the blow-off valves at the beginning of each period. The date and time of each observation are given in Column 3.

Columns 4, 5, 6, 7 and 8 contain the data obtained from the five mercury gauges at Stations Nos. 1, 2, 3, 4 and 5. In each case, the following quantities are entered: Upper scale reading (U), lower scale reading (L), temperature of mercury column (T). In the case of Manometers Nos. 1 and 2, the temperature of the water in the steel pipe (t) is also given. The constant distance between zeros of upper and lower scales is in each case entered at the top of the column. The sub-column headed "Mer." gives the actual height of the mercury column, and the sub-column "Mer. Reduc." gives the height of the mercury column corrected for temperature. In the case of Manometers Nos. 1 and 2 there is a double temperature correction, account being taken of both mercury and water temperatures.



VALUES OF n
0.0200
0.0190
0.0180
0.0170
0.0160
0.0150
VALUES OF c
110.
100.
90.
80.
70.
LOSS OF HEAD PER 1000 FEET
(IN FEET OF WATER)
0.5
0.4
0.3
0.2
0.1
0.
1.0
2.0
VELOCITY (IN FEET PE
LOSS OF HEAD PER THOUSA
1899
1897
A
B
E
G



STEEL
LOSS OF HEAD PER 1000
LOSS OF HEAD PER 1000
CURVES FOR c, n AND LOSS OF H
CURVES FOR LOSS OF HEAD, 189
OBSERVATIONS 1899
Loss O
c
n
VALUES
VALUES OF
LOSS OF HEAD PER THOUSAND FEET
1899
1897
2.0
3.0
VELOCITY (IN FEET PER SECOND)

PLATE VII.
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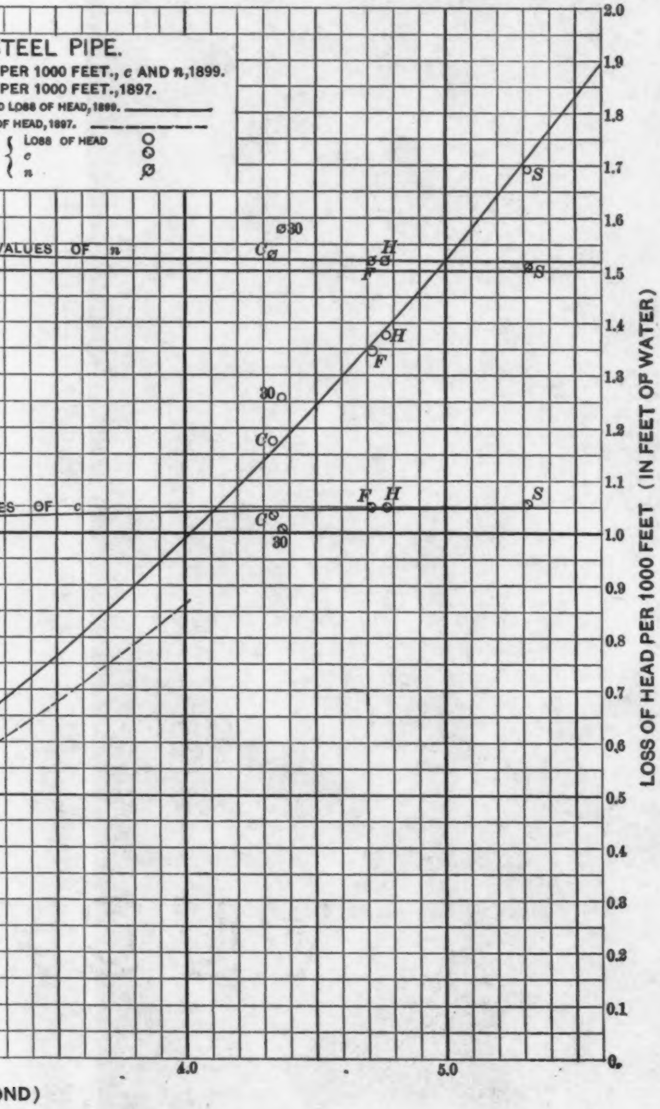


The method of applying the temperature correction may be explained by reference to a single observation, as No. 18. The data entered for Manometer No. 1 are as follows: Upper reading, 2.214; lower reading, 0.033; constant distance between zeros of scales, 31.300; mercury temperature, 10.8° Cent.; water temperature, 11.5° Cent. The actual height of the mercury column is, therefore, $31.300 + 2.214 - 0.033 = 33.481$ ft. To reduce to an equivalent column at 10° Cent. there must be subtracted $33.481 \times 0.00018 \times 0.8 = 0.005$ ft., 0.00018 being the coefficient of expansion of mercury. The correction for water temperature, already explained, has for convenience been applied to the mercury column before reduction to equivalent water column. In Observation No. 18 the temperature of the water in the steel pipe is 1.5° higher than the standard temperature of 10° Cent. The corresponding correction to the mercury column is $33.481 \times 0.000084 \times 1.5 = 0.004$ ft., 0.000084 being taken as the coefficient of expansion of water at temperatures near 10° Cent. The correction for mercury temperature is negative, while that for water temperature is positive; hence the reduced height of mercury column ("Mer. Reduc.") is $33.481 + 0.004 - 0.005 = 33.480$ ft.

It should be remarked that the constant distance between zeros need not be determined with great accuracy. Its only importance is in the computation of the temperature correction.

In Column 9 is given, for each gauge, the height of the "equivalent water piezometer." The datum of reference for each gauge is, as already remarked, arbitrary. If the zero of the lower scale is taken as datum, the equivalent water piezometer height is determined by multiplying the reduced mercury column by 13.57 (the relative specific gravity of the mercury at 10° Cent.), and adding the lower scale reading. Thus, referring to Observation No. 48, the data for Manometer No. 3 are

$$7.136 = \text{reduced height of mercury column;}$$
$$0.006 = \text{lower scale reading.}$$

Hence the height of the equivalent water piezometer is $7.136 \times 13.57 + 0.006 = 96.84$ ft.

In the case of Manometer No. 1, the reduced mercury column is in every case diminished by 30 ft. before the reduction to "equivalent water piezometer." This simplifies the logarithmic computation, and is allowable because it amounts merely to shifting the datum of refer-

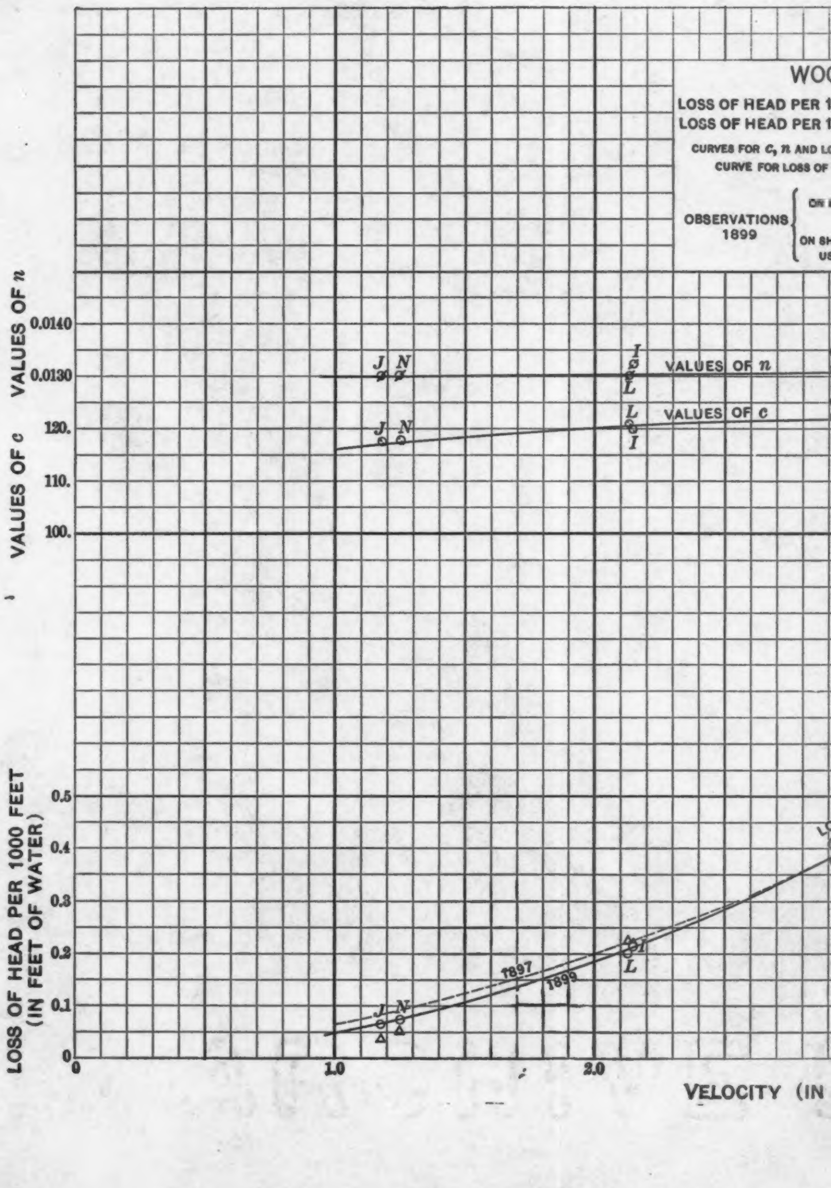
ence by 407.10 ft. (the water equivalent of 30 ft. of mercury). The values of "Mer. Reduc." for Gauge No. 2 have in like manner been diminished by 8 ft.

The sixth sub-column under Column 9 gives the reading of Gauge No. 6. The "equivalent water piezometer" is in this case the actual reading of the gauge. Since the height of water column is only 5 or 6 ft., the temperature correction for this gauge is inappreciable. About 20° change of temperature of the column would be required to change the reading by 0.01 ft.

Sub-column 7, under Column 9, gives the stage of water in the reservoir above the dam. It is obtained by measuring down from a fixed point on the masonry, and the values are therefore given the minus sign. Many of the values entered are obtained by interpolation between observations made an hour or more apart. No special device was used to secure great accuracy in these readings, and in some cases they are affected by an uncertainty of perhaps 0.05 ft. because of waves. These readings are not used in estimating pipe coefficients, but were taken for the purpose of estimating the loss of head in the entire pipe line.

For computing the loss of head between two manometer stations, the difference between simultaneous piezometer columns at these stations is taken. Values of this difference for each of the three lengths of pipe experimented on, and also for Gauges Nos. 4 and 5, are given in Column 10. These values are found in each case by taking differences between the numbers in the corresponding sub-columns of Column 9. The process of computing loss of head is completed by subtracting these differences from the corresponding static difference for each pair of manometers compared. The results are given in Column 11.

Static readings could be secured only during one hour each week, when the water-wheels were stopped. Three sets of static readings were taken, the results being recorded as Observations Nos. 1, 34 and 76. When Observation No. 1 was made, only Manometers Nos. 1 and 2 were ready for use. Observation No. 34 includes readings of all manometers. In Observation No. 76 readings were taken on Manometers Nos. 1, 2, 5 and 6. The static difference for the steel pipe (1–2) was thus observed three times; but as Observation No. 34 on the steel pipe was not regarded as very satisfactory at the time, the static dif-



WOO
LOSS OF HEAD PER 1
LOSS OF HEAD PER 1
CURVES FOR C, n AND LO
CURVE FOR LOSS OF
OBSERVATIONS 1899
VALUES OF n
VALUES OF c
LOSS OF HEAD PER 1000 FEET (IN FEET OF WATER)
0.0140
0.0130
120.
110.
100.
0.5
0.4
0.3
0.2
0.1
0
1.0
2.0
1897
1899
VELOCITY (IN

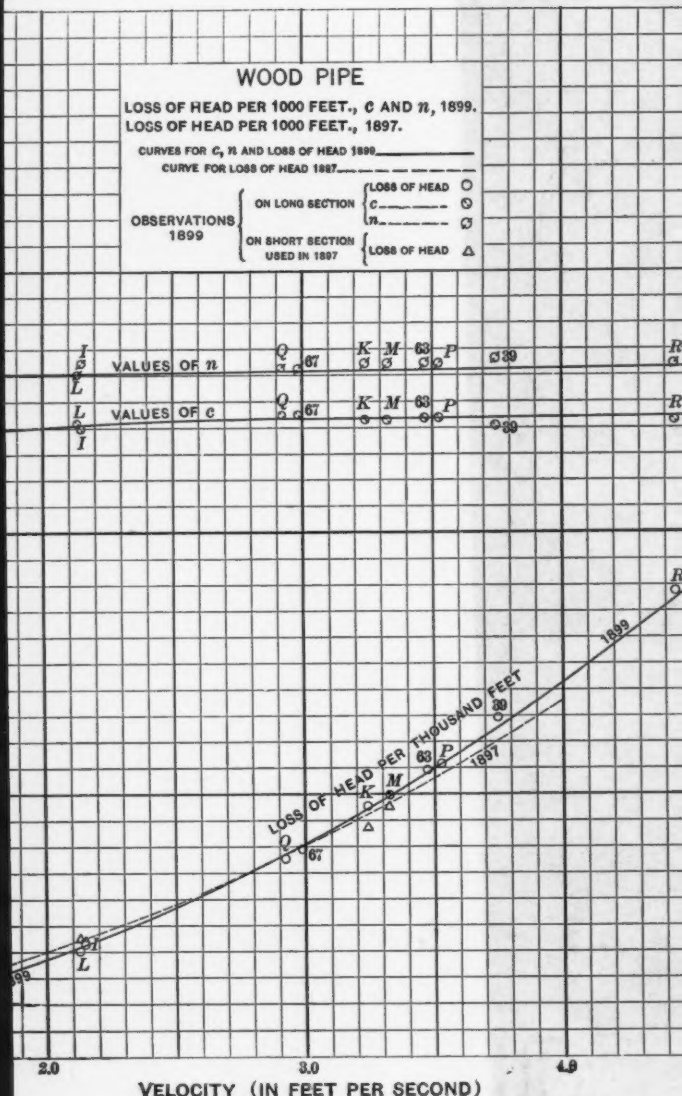

WOOD PIPE
LOSS OF HEAD PER 1000 FEET., c AND n, 1899.
LOSS OF HEAD PER 1000 FEET., 1897.
CURVES FOR c, n AND LOSS OF HEAD 1899
CURVE FOR LOSS OF HEAD 1897
OBSERVATIONS 1899
ON LONG SECTION
LOSS OF HEAD
c
n
ON SHORT SECTION USED IN 1897
LOSS OF HEAD
VALUES OF n
VALUES OF c
LOSS OF HEAD PER THOUSAND FEET
1899
1897
2.0
3.0
4.0
VELOCITY (IN FEET PER SECOND)

PLATE VIII.
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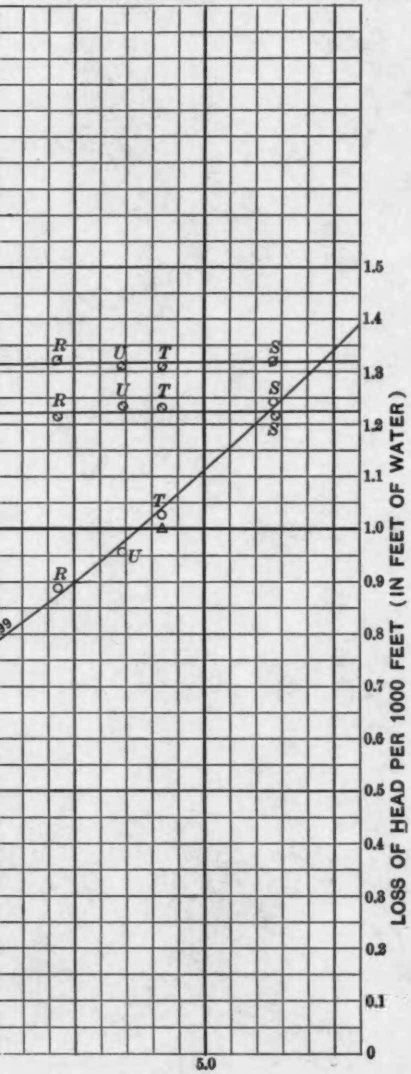

ference adopted for Gauges Nos. 1 and 2 was based upon Observation Nos. 1 and 76, which differ by only 0.01 ft. The two values are 13.19 and 13.18; when the computation is carried to the third decimal place the mean of these is 13.186, and value adopted is 13.19. It will be seen that Observation No. 34 gives a value differing from this by 0.06 ft. If this had been used in computing the mean, the result would have been changed by only 0.02 ft. Only one determination of the static difference 3-4 was made. For 5-6 there were two determinations, giving values 49.49 and 49.55, the mean of which (49.52) was adopted.

In Column 11 are entered the values of the total loss of head and of the loss per thousand feet, for each of the three lengths of pipe 1-2, 3-4, 5-6. At the top of each sub-column is given the length of pipe between manometers. A sub-column is also given for values of the loss between Gauges Nos. 4 and 5, from which the loss due to Tunnel No. 7 may be estimated.

In Columns 12, 13, 14 and 15 are entered the results of the discharge observations. The sub-column headed "gauge" for each meter gives the difference between the heights of the throat and up-stream mercury columns of the Venturi meter difference-gauges. "Head on Venturi" is equal to this difference multiplied by $e-1$, e being the specific gravity of the mercury, 13.57. From this gauge reading and the known dimensions of the meter the rate of discharge is computed, as already explained. The remaining columns, giving rate of discharge for each meter, total rate of discharge, and mean velocity of flow in the steel and in the wood pipe, need no explanation.

In most cases several consecutive observations (usually four) were made with as nearly constant conditions of discharge as possible. When the actual variation was small, such observations were combined into a "group." These groups are designated by letters, which are given in Columns 1 and 17 of Table No. 1 (Plate VI). Table No. 2 shows values of mean velocity and loss of head, as obtained by averaging the results of each group of observations. The other quantities given in this table will be referred to later.

Steel Pipe Results.

The steel pipe results for each observation-group are given in Table No. 2, Columns 3, 4, 5 and 6.

TABLE No. 2.

1	2	3	4	5	6	7	8	9	10	11	12	13
Group.	Steel Pipe. Man. 1-2.					Wood Pipe. Man. 3-4.		Wood Pipe. Man. 5-6.				Total Loss. Man. 4-5.
	Numbers of observations.	Velocity in feet per second	Loss of head per 1 000 ft. in feet.	c.	n.	Velocity in feet per second.	Loss of head per 1 000 ft. in feet.	Velocity in feet per second.	Loss of head per 1 000 ft. in feet.	c.	n.	Total loss in feet.
	1	0.	—0.009	......	......	......	......	......	......	......	......	......
A..	2, 4	0.689	0.059	73.4	0.0198	......	......	......	......	......	......	......
B..	5, 6, 7, 8, 9	1.120	0.121	83.1	0.0182	......	......	......	......	......	......	......
C..	10, 11, 12, 13	4.339	1.177	103.1	0.0153	......	......	......	......	......	......	......
D..	14, 15, 16, 17	3.157	0.645	101.3	0.0157	......	......	......	......	......	......	......
E...	18, 19, 20, 21	2.043	0.286	98.5	0.0157	......	......	......	......	......	......	......
F...	22, 23, 24, 25	4.713	1.343	104.8	0.0152	......	......	......	......	......	......	......
G...	26, 27, 28, 29	2.577	0.423	102.1	0.0154	......	......	......	......	......	......	......
	30	4.375	1.258	100.6	0.0158	......	......	......	......	......	......	......
H..	31, 32, 33	4.779	1.379	104.9	0.0152	......	......	......	......	......	......	......
	34	0.000	—0.000	......	......	0.000	0.000	0.000	0.001	......	......	......
I...	35, 36, 37, 38	......	......	......	......	2.144	0.219	2.144	0.213	119.5	0.0132	0.137
	39	......	......	......	......	3.750	......	3.750	0.644	120.2	0.0133	......
J...	40, 41, 42, 43	......	......	......	......	1.175	0.038	1.175	0.066	117.3	0.0130	0.147
K..	44, 45, 46, 47	......	......	......	......	3.239	0.434	3.239	0.474	121.1	0.0132	0.225
L..	48, 49, 50, 51	......	......	......	......	2.126	0.224	2.126	0.206	120.7	0.0130	0.110
M..	52, 53, 54, 55	......	......	......	......	3.324	0.474	3.324	0.498	121.2	0.0132	0.212
N..	56, 57, 58, 59	......	......	......	......	1.244	0.054	1.244	0.074	117.7	0.0130	0.095
P..	60, 61, 62	......	......	......	......	3.527	......	3.527	0.557	121.7	0.0132	......
	63	......	......	......	......	3.474	......	3.474	0.542	121.4	0.0132	......
Q..	64, 65, 66	......	......	......	......	2.920	......	2.920	0.378	122.2	0.0131	......
	67	......	......	......	......	2.987	......	2.987	0.396	122.2	0.0131	......
R..	68, 69, 70, 71	4.473	......	......	......	4.439	......	4.439	0.889	121.2	0.0132	......
S...	72, 73, 74, 75	5.320	1.696	105.3	0.0151	5.279	......	5.279	1.242	121.9	0.0132	......
	76	0.000	+0.009	......	......	0.000	......	0.000	-0.001	......	......	......
T..	77, 78, 79, 80	......	......	......	......	4.845	1.003	4.845	1.027	123.0	0.0131	0.402
U.	81, 82, 83, 84	......	......	......	......	4.694	......	4.694	0.959	123.3	0.0131	......

The same results are shown graphically in Plate VII. In this diagram mean curves are drawn to represent the relation between mean velocity of flow and each of the three quantities, loss of head per thousand feet, c and n. The curve of loss of head given by the experiments of 1897 is also shown for the purpose of comparison. The later series covers a range of velocities materially greater than the earlier, the greatest value of the mean velocity being 5.32 ft. per second in the observations of 1899 as against 3.85 ft. per second in the series of 1897.

A reference to Fig. 6 of the previous paper * shows that the portion of the curve corresponding to the higher velocities was based largely upon five observations made under conditions of falling press-

* *Transactions*, Am. Soc. C. E., Vol. xl., p. 495.

TABLE No. 3.—STEEL PIPE. GENERALIZED RESULTS.

v.	H'.		c.		f.		n.	
	1897.	1899.	1897.	1899.	1897.	1899.	1897.	1899.
1.0	0.055	0.100	110.0	81.6	0.0212	0.0387	0.0132	0.0184
1.5	0.121	0.177	111.0	92.0	0.0207	0.0303	0.0140	0.0167
2.0	0.220	0.277	110.0	98.0	0.0212	0.0267	0.0144	0.0159
2.5	0.356	0.405	108.0	101.3	0.0221	0.0251	0.0147	0.0155
3.0	0.510	0.570	108.0	102.4	0.0221	0.0245	0.0147	0.0154
3.5	0.673	0.765	110.0	103.2	0.0212	0.0242	0.0145	0.0153
4.0	0.863	0.987	111.0	103.8	0.0207	0.0238	0.0143	0.0153
4.5	....	1.237	....	104.3	....	0.0236	....	0.0152
5.0	....	1.516	....	104.7	....	0.0234	....	0.0152
5.5	....	1.824	....	105.0	....	0.0233	....	0.0152

ure. It seems possible, in the light of the later results, that this portion of the curve is somewhat too low. But making all reasonable allowance for the uncertainty in the values found, it appears that there has been some decrease in the carrying capacity of the steel pipe.

By interpolation, using the mean curves of Plate VII, values of the several quantities may be found for velocities 1, 1.5, etc., feet per second. These generalized values of H', c, f and n are shown in Table No. 3, together with the corresponding values from the observations of 1897.

The Chezy coefficient c shows an increase with the velocity. For velocities above 2.5 ft. per second, this increase, however, is slow, and the upper limit to the value of c would appear to be not greater than 106.

The Kutter coefficient n shows, for low velocities, a decrease with increasing velocity. For higher velocities n approaches a limiting value of about 0.0152.

It must be remembered that the law of variation of c and of n for low velocities cannot be regarded as reliable, because the values found for these quantities are affected very materially by small errors in the measured loss of head.

Wood Pipe Results.

The wood pipe results for all the observation-groups are shown in Table No. 2. For the shorter length of pipe (3–4) the table gives only the velocity and the loss of head per thousand feet (Columns 7 and 8). For the longer portion, values of c and n are also given.

TABLE No. 4.—WOOD PIPE. GENERALIZED RESULTS.

v.	H'.		c.		f.		n.	
	1897.	1899.	1897.	1899.	1897.	1899.	1897.	1899.
1.0	0.066	0.049	100.0	116.0	0.0257	0.0191	0.0150	0.0130
1.5	0.123	0.106	110.0	118.7	0.0212	0.0183	0.0141	0.0130
2.0	0.200	0.184	115.0	119.9	0.0194	0.0179	0.0137	0.0131
2.5	0.292	0.284	119.0	120.8	0.0181	0.0176	0.0133	0.0132
3.0	0.400	0.404	122.0	121.4	0.0173	0.0175	0.0131	0.0132
3.5	0.527	0.548	124.0	121.7	0.0167	0.0174	0.0130	0.0132
4.0	0.678	0.712	125.0	122.0	0.0165	0.0172	0.0128	0.0132
4.5	....	0.898	....	122.2	....	0.0172	....	0.0132
5.0	....	1.105	....	122.4	....	0.0172	....	0.0132
5.5	....	1.335	....	122.5	....	0.0171	....	0.0132

The coefficients c and n and the loss of head per thousand feet are shown graphically in Plate VIII, being plotted as functions of the mean velocity of flow. This diagram shows the observations on both portions of the wood pipe, the two sets of points being marked differently.

As the number of observers was too small to permit the simultaneous occupation of all the six manometer stations, it was thought best to devote special attention to the long section of wood pipe, and to the steel pipe. The number of observations upon the shorter length of wood pipe was therefore limited, their main value being to serve as a check upon the results of 1897, and to show whether any material difference exists between the coefficients for the two portions of wood pipe. The mean curves shown in Plate VIII are intended to represent the results for the long section only. For the purpose of comparing with the previous experiments on the lower section, the mean curve of loss of head as found from the experiments of 1897 is also shown.

The generalized results for the upper section of wood pipe are given in Table No. 4, the values of H', c, f and n being obtained from the mean curves of Plate VIII. The table includes also values of the same quantities for the lower section of pipe, as found from the experiments of 1897.

Loss of Head Due to Tunnel No. 7.

Tunnel No. 7 is 108.7 ft. long, and is unlined, its cross-section being approximately 9 ft. square. Manometer Stations Nos. 4 and 5

were on opposite sides of this tunnel, the former being 23 ft. from its west end and the latter 44 ft. from its east end. Simultaneous readings of the gauges at these two stations furnish date for estimating the loss of head due to the tunnel.

TABLE No. 5.—Tunnel 108.7 Ft. Long. 9 Ft. Square.

Velocity in wood pipe, in feet per second.	Loss between manometers 4 and 5, in feet.	Loss in 67 ft. of wood pipe, in feet.	Loss due to tunnel, in feet.	Equivalent length of wood pipe, in feet.
1.0	0.044	0.003	0.041	835
2.0	0.110	0.012	0.098	532
3.0	0.190	0.027	0.163	405
4.0	0.290	0.048	0.242	340
5.0	0.430	0.074	0.356	322

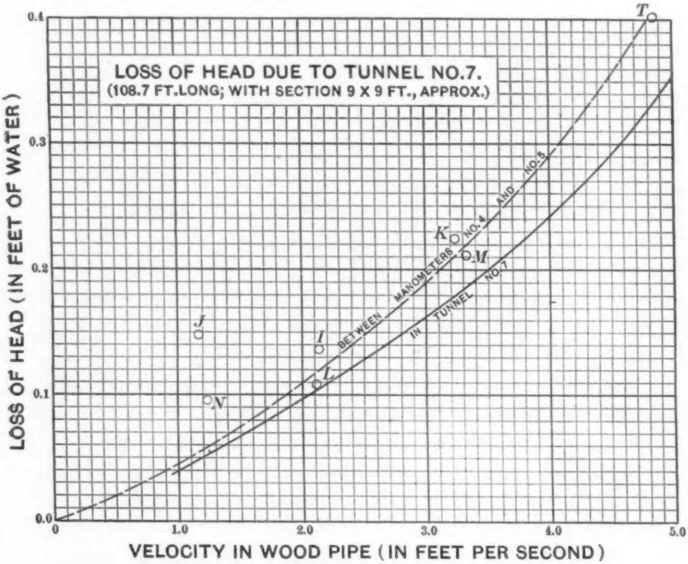

Fig. 3.

The total loss between Gauges Nos. 4 and 5 is given in Table No. 1 (Plate VI), Column 11, and the condensed results are shown in Table No. 2, Column 13. These results are shown graphically in Fig. 3, in which is also drawn a curve to represent the relation between the total

TABLE No. 6.

1	2	3	4	5	6	7	8	9	10
No.	SOUTH METER.		NORTH METER.		Group.	SOUTH METER.		NORTH METER.	
	$\frac{H}{e-1}$	$\frac{H''}{e-1}$	$\frac{H}{e-1}$	$\frac{H''}{e-1}$		$\frac{H}{e-1}$	$\frac{H''}{e-1}$	$\frac{H}{e-1}$	$\frac{H''}{e-1}$
2.....	0.038	0.006	....	....	*A*.....	....	....	....	....
3.....	0.038	0.007	....	....	*A*.....	0.038	0.007	....	....
4.....	0.038	0.007	....	....	*A*.....	....	....	....	....
5.....	0.101	0.020	....	....	*B*.....	....	....	....	....
6.....	0.101	0.019	....	....	*B*.....	....	....	....	....
7.....	0.101	0.019	....	....	*B*.....	0.101	0.019	....	....
8.....	0.101	0.019	....	....	*B*.....	....	....	....	....
9.....	0.101	0.019	....	....	*B*.....	....	....	....	....
10.....	0.659	0.112	0.186	0.030	*C*.....	....	....	....	....
11.....	0.668	0.113	0.184	0.029	*C*.....	0.659	0.111	0.186	0.030
12.....	0.660	0.112	0.187	0.031	*C*.....	....	....	....	....
13.....	0.648	0.108	0.186	0.030	*C*.....	....	....	....	....
14.....	0.582	0.099	0.027	0.003	*D*.....	....	....	....	....
15.....	0.556	0.094	0.027	0.002	*D*.....	0.546	0.091	0.027	0.003
16.....	0.537	0.090	0.027	0.003	*D*.....	....	....	....	....
17.....	0.510	0.082	0.027	0.003	*D*.....	....	....	....	....
18.....	0.345	0.058	....	....	*E*.....	....	....	....	....
19.....	0.331	0.056	....	....	*E*.....	0.341	0.058	....	....
20.....	0.331	0.056	....	....	*E*.....	....	....	....	....
21.....	0.358	0.061	....	....	*E*.....	....	....	....	....
22.....	0.816	0.138	....	....	*F*.....	....	....	....	....
23.....	0.815	0.137	....	....	*F*.....	0.813	0.137	....	....
24.....	0.812	0.136	....	....	*F*.....	....	....	....	....
26.....	0.544	0.091	....	....	*G*.....	....	....	....	....
27.....	0.544	0.091	....	....	*G*.....	0.545	0.092	....	....
28.....	0.546	0.095	....	....	*G*.....	....	....	....	....
31.....	0.506	0.087	....	....	*H*.....	0.506	0.087	....	....

loss of head between gauges and the mean velocity of flow in the wood pipe. Upon this curve are based the generalized results given in Table No. 5.

The total length of wood pipe between the two gauges is 67 ft.; the loss of head due to this length, assuming the loss per thousand feet to have values as given in Table No. 4, is computed and entered in Table No. 5. Deducting this from the total loss between gauges, the loss due to the tunnel is found. The total tunnel loss is made up of loss at entrance, loss at outlet, and loss due to resistances in the tunnel itself. It is not possible to estimate these losses separately so as to determine the value of c for the tunnel. The curve showing total loss due to tunnel for different values of velocity in the wood pipe is given in Fig. 3.

The last column of Table No. 5 shows the length of wood pipe which would produce the same loss as the tunnel.

Loss of Head in Venturi Meters.

A limited number of observations was made on the loss of head due to the Venturi meters. The first and third tubes of each of the triple difference-gauges communicated with the pipe at points where the values of the mean velocity were equal, the diameter being 54 ins. at each section. The observed pressure-difference between these sections, therefore, was due wholly to the loss of head in the intervening portion of the stream.

It should be stated that this observed loss is not all chargeable to the meter. The portion of the pipe between the two pressure sections included, besides the converging and diverging portions of the meter, about 7 ft. of 54-in. riveted pipe. The diverging pipe below the throat is constructed of riveted plates, and a gate-valve, occupying

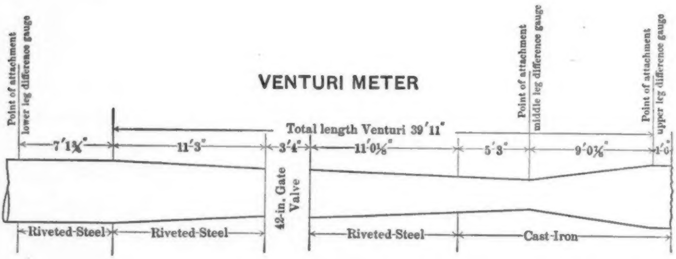

FIG. 4.

about 40 ins., is situated in this portion of the pipe. The whole arrangement is shown in Fig. 4. Doubtless, the greater part of the observed loss of head occurred between the throat and the down-stream pressure section. While the loss in the diverging pipe may be properly charged to the meter, since this is a necessary part of the apparatus, this is not true of the loss in the 7 ft. of 54-in. pipe below, nor of the loss due to the gate. The points of attachment of the difference-gauge tubes were the same in these experiments as in the previous series.

The results of the observations on the loss of head in the meters are shown in Table No. 6. "Head on Venturi" is denoted by H, and "loss of head" by H''. The specific gravity of the mercury being e, the difference between the up-stream and throat mercury columns is

$\frac{H}{e-1}$, and the difference between the up-stream and down-stream columns is $\frac{H''}{e-1}$. These are the quantities observed directly, and the observed values are given in the table. These values are averaged in groups, and the average values are entered in Columns 7, 8, 9 and 10. The observation numbers and the letters designating groups agree with those in Table No. 1 (Plate VI).

The results are plotted in Fig. 5. As in the previous series of observations,* the plotted points fall very nearly on a straight line, indicating a relation expressed by the equation $H'' = a\,H$, with a constant value of a. The value found for a is 0.169, while in 1897 the value was 0.149. The lines corresponding to both these values are shown in Fig. 5.

It thus appears that the loss of head between the two sections compared increased 13.4% between August, 1897, and June, 1899. This is on the assumption that the loss of head in the meter proper (*i. e.*, between the upper section and the throat) has remained constant; for unless this is true a given value of "head on Venturi" corresponds to different values of the rate of discharge in the two series of experiments.

How nearly correct this assumption is, there are no means of knowing. It is probable, however, that the change in the loss in the converging part of the meter is slight.

It may be pointed out that an increase of 13.4% in the loss of head, for any given velocity, agrees well with the increase observed in the 72-in. steel pipe. This may be verified by a comparison of the 1897 and 1899 curves of loss of head in Plate VII.

The continued courtesy of C. K. Bannister, M. Am. Soc. C. E., Chief Engineer of the Union Power Company, and of the Board of Directors, enabled the writers to duplicate and extend the series of observations made in 1897. To them and to Mr. L. S. Boggs, Electrical Engineer, the writers are under great obligations for giving *carte blanche*, so far as they were able to do so without interfering with the running of the plant. As the writers were short-handed at times, the work could not have been carried through in the time at their disposal if the Superintendent of the Power Company, Mr. C. E. Crocker,

* See Figs. 13 and 14 of previous paper.

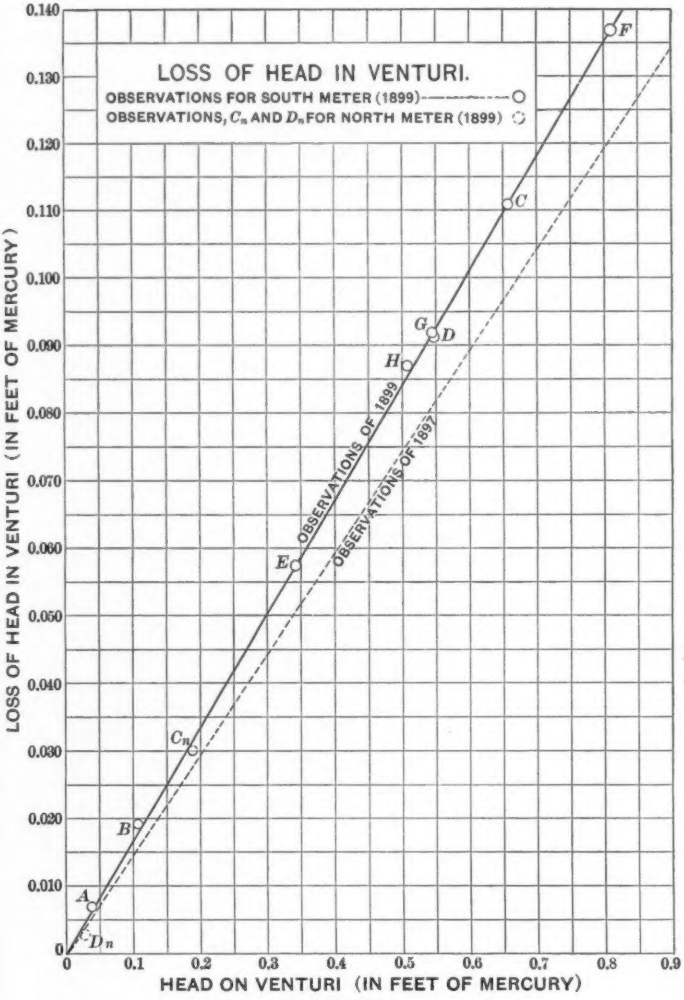
LOSS OF HEAD IN VENTURI.
OBSERVATIONS FOR SOUTH METER (1899)
OBSERVATIONS, C_n AND D_n FOR NORTH METER (1899)
OBSERVATIONS OF 1899
OBSERVATIONS OF 1897
A
B
C_n
D_n
E
H
G
D
C
F
0.140
0.130
0.120
0.110
0.100
0.090
0.080
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
LOSS OF HEAD IN VENTURI (IN FEET OF MERCURY)
HEAD ON VENTURI (IN FEET OF MERCURY)

Fig. 5.

had not kindly assisted in taking readings. He also regulated the discharge so as to give, so far as practicable, the desired velocities. For his assistance and co-operation the writers desire to express their sincere thanks. Their former assistant, Mr. L. B. Spencer, Assistant Engineer, Oregon Short Line, came from Salt Lake on two occasions to help, and to him also the authors owe thanks. During the entire period of their stay they were, furthermore, assisted by their colleague, Professor J. C. L. Fish, who has added to their obligations by preparing a number of the diagrams which accompany this paper.

DISCUSSION.

E. Kuichling, M. Am. Soc. C. E.—One of the most interesting features of this paper is the comparison of the observations made by the authors in 1897 on the large riveted-steel pipe with those made by them in 1899. From this comparison, as exhibited in Table No. 3, they conclude that during the period of two years there has been some decrease in the carrying capacity of this pipe. A similar, although much smaller, reduction is also noticeable in the case of the large wooden pipe, for velocities of 3 ft. and upward, as shown in Table No. 4. The data submitted are very important to hydraulicians, as it rarely happens that the same line of pipe is tested by the same competent and careful observers at different periods of time. Mr. Kuichling.

In the speaker's opinion, such a decrease in carrying capacity is always to be expected, and, so far as he has been able to ascertain from the records of reliable gaugings made by others, as well as by himself, it has always occurred, especially in the case of cast and wrought-iron or steel pipes. Two principal causes therefor can be assigned, viz., the gradual formation of nodules of rust, or "tubercles," and the accretion of various organic growths on the inner surface of the conduits. Either of these developments must obviously increase the resistance to the flow of the water in the pipe, and hence also diminish the discharge. The first-named cause is necessarily excluded in the case of a wooden conduit, but in an iron or steel pipe both causes may exist simultaneously.

Rust, or tuberculation, in a water pipe is the result of the action of the water upon the iron, wherever exposed, by defects or abrasions of the protective coating. The area of the imperfection may be very small or even microscopic in size, but its site will sooner or later be manifested by the appearance of a yellowish brown pimple, which gradually increases in size and ultimately assumes relatively large dimensions by spreading laterally over the adjacent sound coating material. Two or more neighboring accumulations of this kind frequently merge into a single large crust, and, when it is forcibly removed, the few minute sources of the supply of hydrated iron oxide are often readily discernible. This oxide evidently attracts or unites with some of the earthy and mineral matter in the water, and the resulting mixture becomes quite coherent, besides adhering more or less strongly to the inner surface of the pipe. In this manner a tubercle is slowly formed, and when the earthy matter preponderates over the iron oxide, it may also become the seat of an extensive organic growth, thereby increasing its size and the degree of obstruction to the flow.

As already stated, the organisms which may lodge and develop in a

Mr. Kuichling. pipe are of various kinds, and may be of either animal or vegetable character, but adapted to the absence of sunlight and free air. They generally grow on the sides and top of the conduit, and rarely on the bottom, as they appear to dislike the subsidence of fine silt which is apt to occur when the velocity of the water is either greatly reduced, or entirely stopped by entrainment in the branches. Several species of polyzoa, spongilla and algæ, or fungi, were found easily by the speaker in searching for them in dark chambers of reservoir gate-houses and also in the conduits and distributing pipes of several different water-works, but in the latter they were usually restricted to the upper portion of the line or to the vicinity of the source or reservoir. In some cases, however, these growths were found in pipes at a distance of several miles from the head.

An instructive instance of this kind was observed recently in the new conduit of the Rochester, N. Y., water-works. The northern section thereof is about 9 miles long, and consists of about 1 000 ft. of 36-in. cast-iron pipe, beginning at Rush Reservoir, followed by 38-in. riveted-steel pipe for the remainder of the distance to the city. A number of gaugings of the flow of this section, and measurements of the loss of head in the cast-iron and steel pipes separately, have been made as carefully as was possible, by the same corps of assistants, since its completion in 1894, and the essential results of these experiments are given in Table No. 7.

TABLE No. 7.—Results of Gaugings of the Northern Section of the New Conduit of the Rochester, N. Y., Water-Works, by the Same Parties, at Different Times between October 17th, 1895, and November 10th, 1899.

No. of gauging.	Date.	Duration of experiment, in hours.	Observed hydraulic grade in the 36-in. cast-iron pipe.	Observed hydraulic grade in the 38-in. riveted-steel pipe.	Observed mean velocity in the 36-in. cast-iron pipe, in feet per second.	Observed mean velocity in the 38-in. riveted-steel pipe, in feet per second.	Deduced coefficient (c) in $v = c\sqrt{rs}$ for the 36-in. cast-iron pipe.	Deduced coefficient (c) in $v = c\sqrt{rs}$ for the 38-in. steel pipe.	Mean age of the conduit in service, in years.
	1895.								
1..	Oct. 17...	5.35	0.0013876	0.0015866	4.204	3.876	129.45	109.35	1.28
2..	Oct. 26...	5.22	0.0015066	0.0016137	4.239	3.908	125.25	109.34	1.30
3..	Nov. 7....	6.38	0.0015034	0.0016180	4.234	3.904	125.25	109.07	1.36
	1897.								
4..	July 28..	10.77	0.0022774	0.0016250	4.128	3.806	99.22	106.11	3.06
5..	Nov. 11..	7.92	0.0048187	0.0015315	4.045	3.730	66.84	107.11	3.35
6..	Nov. 19..	7.08	0.0048535	0.0015334	4.023	3.709	66.24	106.46	3.37
	1898.								
7..	June 4...	8.95	0.0043408	0.0015655	4.034	3.719	70.23	105.65	3.91
8..	Dec. 21...	8.00	0.0037591	0.0015531	4.026	3.712	75.32	105.86	4.47
	1899.								
9..	July 25...	8.00	0.0034455	0.0015349	4.084	3.765	79.79	108.00	5.04
10..	Nov. 10..	8.00	0.0032585	0.0015424	4.077	3.759	81.93	107.58	5.34

Mr. Kuichling.

It should be noted that the actual mean diameter of the 36-in. cast-iron pipe is 3.0406 ft., as deduced from four measurements of the bore of each separate piece before being set in place, while that of the inside courses of the 38-in. riveted-steel pipe is 3.1667 ft.; also that the corresponding cross-sectional areas are, respectively, 7.2612 and 7.8758 sq. ft., and the lengths between the end piezometers, respectively, 1 094.3 and 45 393.9 ft. The difference in level between the piezometer vessels was determined instrumentally, while the volume discharged by the pipe in the given periods of time was computed from the observed fall in the water surface of the large reservoir at the head of the section, the area for different elevations being known. The water to supply the piezometers was taken in each case from a standard corporation cock screwed squarely into the cast-iron pipe at or near its top. Furthermore, at the distributing reservoir in the city, the steel conduit terminates with about 250 ft. of 36-in. cast-iron pipe, but the length thereof which is embraced, up to the lower piezometer, is included in the 1 094.3 ft. mentioned.

When the extremely low value of the coefficient c for the 36-in. pipe in Gauging No. 5 became known, it was assumed that an error had been made, and the work was repeated a few days later, with practically the same result, as shown in Gauging No. 6. Special care having then been taken to avoid errors of observation, it was conjectured that the reduction was due to a profuse growth of aquatic organisms in this part of the line, such as was found in the 24-in. effluent pipe of the old conduit at the same locality when a part of it was removed in 1894 for connection with the new pipe. A corroboration of the accuracy of the observations in Gaugings Nos. 5 and 6 was also afforded a few months later by Gauging No. 7.

To ascertain whether this conjecture was correct, an examination of the interior of the pipe was made in September, 1898. The flanged head of a 36-in. special casting in the new gate-house at Rush Reservoir was accordingly removed, and the 36-in. cast-iron pipe was entered and traversed by an assistant for a distance of about 450 ft., while the 38-in. steel pipe was entered at a manhole 3 498 ft. north of the gate-house and traversed for 100 ft. or more in both directions. Owing to the existence of several depressions in the line between these points of entry, and the necessity of soon restoring the new conduit to active service, no further investigations of the intermediate parts of the pipe were made.

On entering the 36-in. cast-iron pipe in the gate-house, extensive organic growths were seen attached to the top and sides, while the lower part was considerably tuberculated. These growths soon increased in magnitude until they formed an almost continuous lining for the entire distance traversed, with frequent large masses hanging down from the top. A number of such pieces were noticed, which were

Mr. Kuichling. more than 1 ft. square, stretching like curtains across the upper part. The lining, in general, resembled a dense fibrous mat from 1 to 2 ins. thick, and the glossy pitch coating of the pipe was visible only in a few places. Further examination showed that these growths consisted mainly of two species of polyzoa and one of fresh-water sponge, which were identified by Professor Charles W. Dodge, of the University of Rochester, N. Y., as *Plumatella*, *Paludicella* and *Myenia fluviatalis*. At the point where the 38-in. steel pipe was entered, the organic growths and tuberculation had greatly diminished in both size and extent, as only a few scattering patches, from 2 to 8 ins. in diameter, and not exceeding ½ in. thick, were found, along with some small tubercles. The latter were on the lower part of the pipe in the immediate vicinity of the manhole, and doubtless resulted from the abrasion of the coating by the shoes of the workmen during construction. Elsewhere, the coating was clean, hard and glossy, and apparently as sound as when first applied. Several attempts were made to obtain photographs of the interior of the pipe by flash light at the localities mentioned, but unfortunately all the negatives, on being developed, proved to be dim and imperfect. The foregoing verbal description must therefore suffice to convey an approximate notion of its condition, and hydraulicians will doubtless require no further reasons for the low values of the coefficient c in the Chezy formula which were found from the gaugings relating to the comparatively short section of cast-iron pipe.

From this examination of the conduit, it will be seen that the luxuriant organic growths were limited to perhaps 1 000 ft. or more of the upper part of the line, while the formation of tubercles is possible for its entire length. The reason for such restriction of the extent of the former is obviously found in the fact that the food supply for the organisms, which is contained in the water, is correspondingly limited and becomes practically exhausted beyond a certain distance from the source; hence, in the lower part of the line no organic growths will probably be found. It may therefore be concluded that the gradual diminution of the carrying capacity of a pipe by the development of aquatic organisms on its interior is dependent on the quality of the water, and that when the proper food supply is scanty, little trouble from this cause will be found in a long conduit. On the other hand, there is no such natural limitation to the formation of rust in an iron pipe which is not provided with an absolutely perfect protective coating; and as such a coating has hitherto been practically unattainable, it follows that a reduction of discharge due to this second cause must reasonably be anticipated.

Returning to the case of the Ogden conduit, which was put in service early in 1897, and whose present interior condition is unknown, it is very probable that while no appreciable quantity of organic growths may exist in the steel pipe which forms the lower

portion of the long line, there may yet be sufficient tuberculation to account for the reduced discharging capacity which was found by the authors. Two years' time is sufficient for the purpose, when it is remembered that the asphaltic coating was applied by hand, and that numerous imperfections in such work are inevitable, notwithstanding the most rigid inspection. Proof of this conjecture, however, is lacking, and it is therefore to be hoped that the authors will at some future time supplement their present valuable contribution to hydraulics by a third series of gaugings, in which an opportunity to examine the condition of the interior of the conduit will be afforded. Mr. Kuichling.

Another interesting point in the paper is the considerably increased loss of head in the Venturi meters, upon whose registration dependence is placed for obtaining the discharge and mean velocity in the conduit. The authors have assumed that the loss of head in the meter proper has remained constant, but were unable to verify this assumption. Should it be found by experiment that a change in the frictional resistance of the two tapering sections of riveted pipe which constitute the meter will modify the empirical constant used in computing the discharge, as is by no means improbable, the given numerical values of the Chezy coefficient *c* will also require suitable modification; and hence, in conducting another series of gaugings, the means for testing the registration of the meters should also be included.

G. C. Whipple, Assoc. M. Am. Soc. C. E.—The growth of microscopic organisms in water is, certainly, an important subject, because such growths have a marked effect upon the flow in pipes. These organisms are likely to grow in pipes whenever the water flowing therein contains a sufficient amount of food to nourish them. Mr. Whipple.

The polyzoa, fresh-water sponge, etc., are sedentary forms which grow on the sides of the pipe, and must have their food carried to them. If the water contains the right kind of food to nourish them it is quite likely that they will thrive in any kind of a pipe. The whole subject is chiefly a question of food supply.

For example, in Newton, Mass., which is supplied with a groundwater containing practically no microscopic organisms, an examination of the pipes showed that there were very few polyzoa. In Boston, on the other hand, where the water contains these microscopic forms, many of the pipes were found to be filled with them.

The presence or absence of these organisms can be accounted for, to a great extent, by the microscopical character of the water itself. It is possible that the water flowing in the Ogden pipe-line may be so free of the smaller microscopic organisms that none of the sedentary organisms are present in any part of the pipe-line, while the water may be of such a character as to cause tuberculation of the steel pipe, without having any such chemical action on the wooden pipe.

Mr. Whipple. It would be interesting to know whether the authors made any examination of the quality of the water flowing through the pipe, and whether any opportunity was offered them to examine the pipe-line with reference to the presence of polyzoa, fresh-water sponge and other similar organisms.

Mr. Meem. JAMES COWAN MEEM, Assoc. M. Am. Soc. C. E. (by letter).—In comparing the steel pipe tests for 1897 and 1899, it is noted that with clean pipes, in 1897, the value of the coefficient of roughness n was not only much lower, but was also much more uniform than in 1899, when the pipe had undoubtedly become tuberculated with rust and growths. It is undoubtedly a valuable increment to our knowledge to find that with tuberculated pipes the value of n seems to decrease in proportion to the rise of velocity, below, and up to 3 ft. per second; while, for practical purposes, it may be considered as constant under the same conditions for clean pipes under all velocities.

This latter point is borne out by the 1899 experiments on the wood-stave pipes, which show a constant value for n for all velocities; and it is further borne out by some crude experiments made by the Sewer Department of Brooklyn, in 1896, on the 15-ft. brick sewer on Fourth Avenue, which also showed a practically constant value for n under varying velocities.

The comparison between the 1897 and 1899 experiments on the wood-stave pipe shows a marked decrease in the value of n after two years' use. This doubtless shows that organisms require more, as Mr. Whipple suggests, than that their food be brought to them, but that they must also have a "lodging place," which is probably furnished in the steel and iron pipes by the commencement of rust, and points to the further fact that wood pipe seems to wear smoother with usage. Arthur L. Adams,* M. Am. Soc. C. E., states that the growths in wood pipe are not found to exist where the pipe is constantly full and under pressure. It is probable, then, that the presence of decay only in this pipe furnishes the nucleus about which these organisms grow.

Comparing these experiments with those noted or made by Mr. Adams,† it is seen that the value of n is much lower in the stave pipes of smaller sizes. Thus, in the 72-in. pipe in the paper it is 0.0131, while in the experiments by Mr. Adams on 14-in. and 18-in. pipes, $n = 0.010$ for the 18-in., and 0.0107 to 0.011 in the 14-in. pipe. This confirms substantially what the writer has long believed to be true, that in pipes of small diameters, all else being equal, the value of n is lower than for pipes of large diameter. Comparison of the experiments referred to, on the 15-ft. brick sewer in Brooklyn (which though crudely made showed the value of n to be between 0.013 and 0.015), with some other experiments‡ made by T. C. Hatton, M. Am. Soc. C. E., of Wil-

* *Transactions*, Am. Soc. C. E., Vol. xli, p. 84.

† *Transactions*, Am. Soc. C. E., Vol. xli, p. 55.

‡ Published, the writer believes, in *The Engineering Record*.

mington, Del., on small pipes (in which the value of n was shown to be materially lower than 0.013) partially confirms this conclusion, although not decisively or definitely enough to be of value, as they were not compared under the same conditions. Mr. Meem.

The summary of these deductions is as follows:

(*a*) In smooth pipes of the same size and kind the value of n is practically constant under all velocities.

(*b*) In tuberculated pipes under all high velocities the value of n is constant, for the same sizes and conditions; while

(*c*) In tuberculated pipes, for the same conditions, under low velocities, the value of n increases inversely with the velocity.

(*d*) In clean pipes the value of n probably decreases with the diameter of the pipe, other conditions being the same.

In assigning the value of n, in estimating or calculating the velocities in proposed pipes and conduits, it is, of course, beyond the range of possibility to test the proposed pipes under the exact conditions of usage; or to find experiments fitting each case exactly. The writer, therefore, proposes a factor of safety, as in construction, which may be used at the discretion of the engineer. As our tables and diagrams are usually calculated for a value of 0.015 for n, we may take this as a basis on which the following factors of safety are suggested for adoption:

(1) For steel-riveted or cast-iron pipes, calculated to run under low velocities, or which are inaccessible for cleaning, add 20% to the total discharge in making the final calculations for sizes.

(2) For steel-riveted or cast-iron pipes, under high velocities, or which are accessible for cleaning, add 10 per cent.

(3) For brick, concrete and pipe conduits, under all velocities, and of over 3 ft. in diameter, or wood-stave pipe alternately wet and dry, add nothing.

(4) For small pipes of all kinds except iron or steel, and wood-stave pipes of over 3 ft. diameter, and running full at all times, deduct 10 per cent.

(5) For wood-stave pipes of less than 3 ft. diameter, constantly full and under pressure, deduct 20 per cent.

Gardner S. Williams, M. Am. Soc. C. E. (by letter).—The authors are to be congratulated upon having performed the most accurate series of experiments yet published upon wooden-stave pipe. Their observations upon the riveted pipe do not, however, appear to be quite so reliable, either from unsuspected sources of error in the methods and means of observation, or, much more probably, on account of conditions in the pipe line itself which prevent the general application of the results obtained from it; so that, while the conclusions which may be drawn from them may not be suitable for common use, the experiments themselves, for the particular case in hand, may Mr. Williams.

Mr. Williams. be in every way as accurate and deserving of confidence as those upon the upper section of stave pipe, which the writer believes will compare favorably with the best pipe experiments yet published, and which appear to be of wide application. The reasons for this differentiation of the results will be discussed later. Before proceeding with this question, however, there are other points in the paper which should be considered.

The authors (page 37) argue that in order to have the gauge readings vitiated by accumulations of air in the connections, there must be present a quantity sufficient to fill the cross-section of the pipe completely. It appears to the writer that any mixture of air and water must have a less specific gravity than water alone, and hence, if even minute bubbles of air be present in a connection rising to a gauge, the effect will be to cause the gauge to read high. As this very principle has long been utilized in the old forms of air-lift pumps, it does not seem necessary to discuss it further than to say that if the connecting pipe slopes downward to the gauge, the result will be a low reading, and that while very few, if any, of the present observations give evidence of such a source of error, the fact remains that observations may be affected by air which does not fill the cross-section of the pipe.

On the same page the authors refer to observations with piezometers connected at various points in the circumference, from which they appear to conclude the correctness of the very interesting theoretical discussion of this subject presented in their former paper.*

On this point the writer has to submit that he knows of experiments with very delicate apparatus for measuring the pressures at different points of the circumference of a pipe in which water was flowing, which showed that the pressures not only are different at different points, but that they change sign relatively to each other as the velocity changes, one becoming alternately greater and less than the other at the opposite extremity of the same diameter. As it is expected that these experiments will shortly be presented to the Society, with some others on the flow of water in pipes, the writer does not wish to go into detail here, but it seems to him entirely safe to conclude that the hypotheses assumed by the authors in their former discussion were contrary to fact, and that in the present case, had they had more delicate apparatus, they would probably have found a difference in the readings at the several points of the circumference.

In reference to the general results, it is always desirable to have some criterion by which to judge of the accuracy of experiments as they are published, aside from that of the personality and reputation of the observers; and the writer has for some time been in the habit of applying to his own observations the following:

* *Transactions*, Am. Soc. C. E., Vol. xl, p. 522.

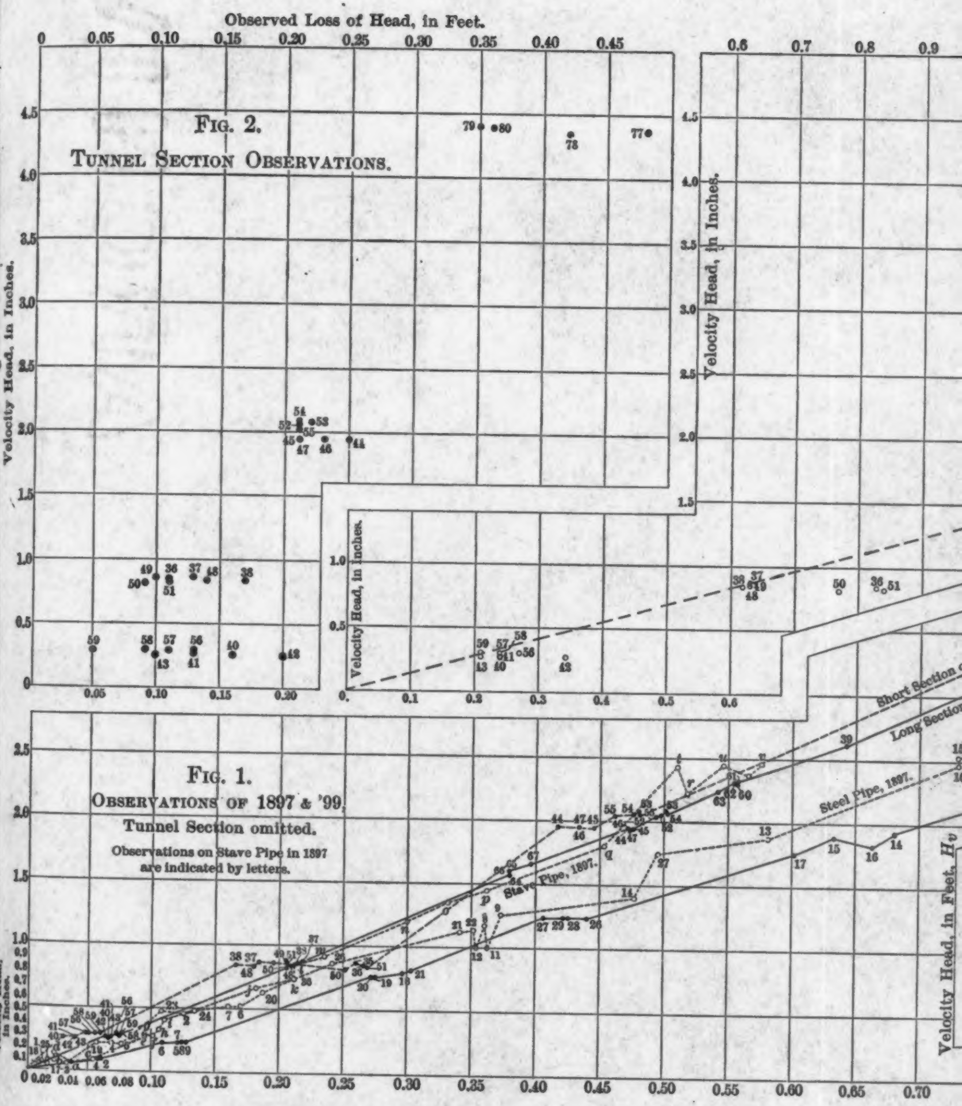

FIG. 2.

TUNNEL SECTION OBSERVATIONS.

FIG. 1.

OBSERVATIONS OF 1897 & '99.

Tunnel Section omitted.

Observations on Stave Pipe in 1897 are indicated by letters.

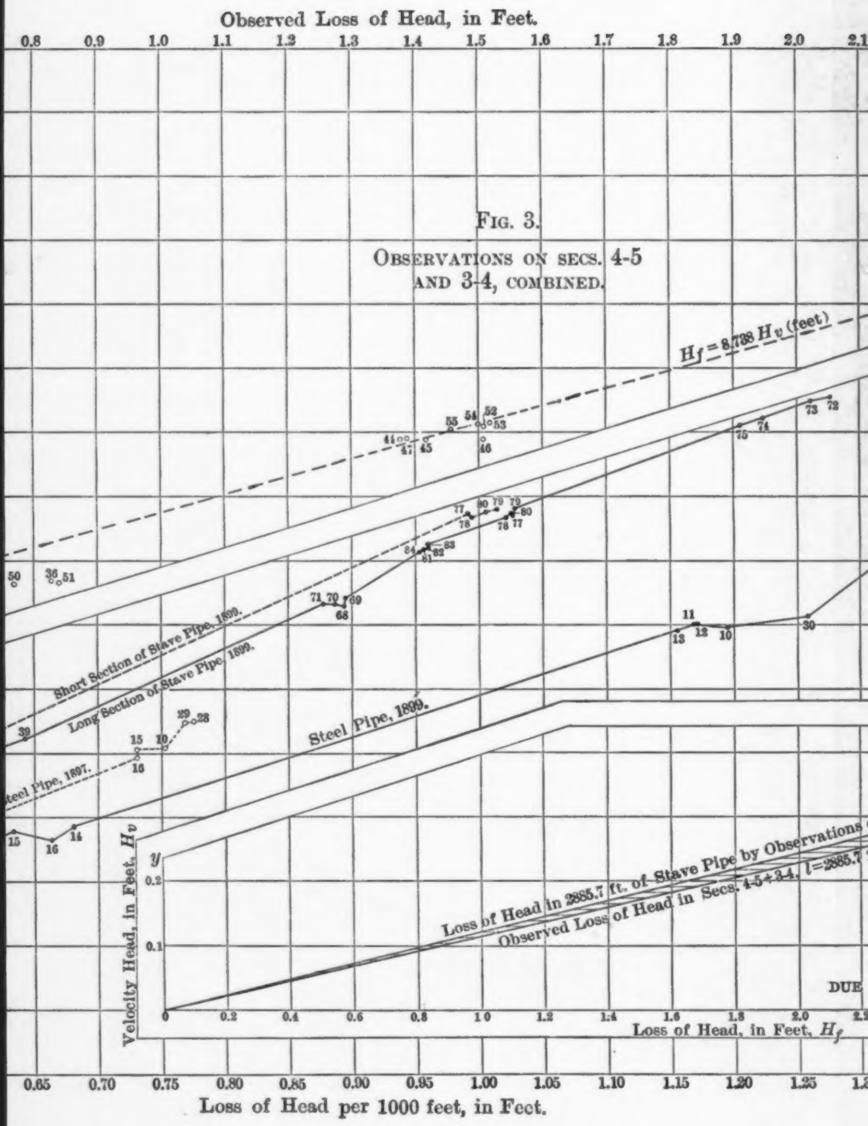

FIG. 3.

OBSERVATIONS ON SECS. 4-5 AND 3-4, COMBINED.

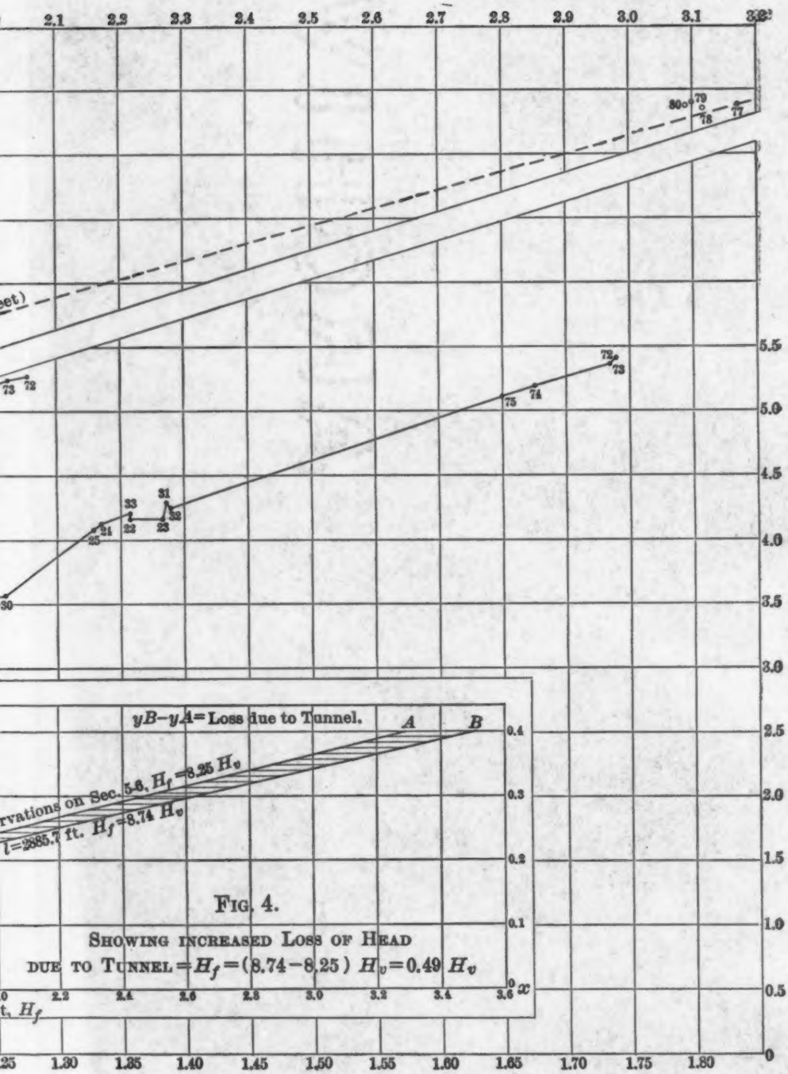

FIG. 4.

SHOWING INCREASED LOSS OF HEAD DUE TO TUNNEL $= H_f = (8.74-8.25)\ H_v = 0.49\ H_v$

Mr. Williams.

Assuming that the loss of head varies as the square of the velocity, the former must also vary as the first power of the velocity head; whence, in any series of experiments covering more than one velocity, if the velocity heads and the corresponding losses of head be used as co-ordinates, theoretically, the points so located should fall in a straight line which may be expected to pass through the origin; and the deviation of the points so plotted from such a line will indicate the relative merit of the several observations. It will at once be appreciated that while some form of curve can usually be made to pass through and fit fairly well a great many observations, it is not such an easy matter to fit a straight line to them.

This criterion has been applied by George H. Fenkell, Jun. Am. Soc. C. E., to nearly all the so-called standard pipe experiments hitherto published, and it is somewhat surprising to see how many supposedly reliable observations are nothing more than crude approximations. It is hoped that Mr. Fenkell's work may soon be given to the public in order that the records may be purged of a considerable number of experiments which should never have been published, and that the relative merits of others may be estimated properly.

An application of this criterion to the observations of the authors in 1897 showed that the high degree of accuracy claimed by them, based upon reductions by the method of least squares, was frequently imaginary.

In Fig. 1, Plate IX, the writer has plotted the observations presented in Table No. 1 (Plate VI) of the present paper, and also the data of the previous series of experiments. To avoid unnecessarily complicating an already rather intricate diagram, the straight lines to which the observations should conform have not been drawn, but if a fine thread be stretched along the line of observations for the long section of stave pipe, the excellence of the results will be at once apparent, and if the equation of the mean line be computed by summations of the ordinates and abscissas we obtain $H_f = 2.8643\ H_v$, where H_f is the loss of head and H_v is the velocity head, measured in feet.

Similarly, if the thread be stretched along the points for the short section of stave pipe, which are united by the fine broken line it will not only be seen that the inclination of the line is not the same as in the other case, but also that the points do not fit as well, and that, in fact, this series of observations appears to be very little better than those of 1897, which are indicated by letters and joined by the dotted lines.

Observations Nos. 40, 41, 56, 57, 58, 59, 37, 38, 48 and 44, seem to show too low a loss of head as compared with the velocity head, while 35, 36, 50 and 51, show the opposite condition. Excepting the four last named, it appears that in this section of pipe the observations at low velocity indicate a much lower resistance than corresponding observations on the longer section, a result which, while it does not

Mr. Williams. accord with the former observations on this section, as indicated by *A*, *B*, *C*, *D*, *E*, *G*, *H* and *K*, is seemingly correct.

Remembering this condition of affairs in Section 3–4, we now consider the Tunnel Section 4–5, the observations upon which are plotted in Fig. 2, Plate IX. By stretching the thread here it will be seen that the observations fail to have the semblance of conformity to the straight line, and it appears that all the observations at low velocities show abnormally high losses of head, exactly the opposite condition to that observed in the section next down stream, already considered. These facts seem to indicate that the piezometer at No. 4 gave a low reading, particularly at low velocities. Without attempting to account for this at present we will combine the total losses of head in Section 4–5 with the simultaneous ones in Section 3–4, and plot the combined result to the velocity heads in the stave pipe, which plotting is shown in Fig. 3, Plate IX. In this figure, the mean line obtained by summation of ordinates has been drawn, Nos. 42, 50, 36 and 51 being rejected. It is to be remarked that Nos. 36, 50 and 51, seem to contain errors of observation or reduction, but as they were grouped by the authors with others this point does not attract especial attention in their plottings, although quite evident here. The close approximation of the remaining observations to the straight line, except perhaps No. 46, is quite remarkable, although there is still a tendency for the low velocities to show excessive loss of head, which has no counterpart in the observation on the long section of stave pipe.

The following explanation of the phenomenon might not have been so obvious, but for the fact that a similar one was encountered recently by Messrs. E. C. Murphy and C. C. Torrance, their observations being corroborated by the writer, in the Hydraulic Laboratory of the College of Civil Engineering of Cornell University, where such precautions were taken as to leave no possibility of questioning the results.

All are familiar with the fact that when water flows from the bottom of a vessel to a pipe of smaller cross-section, a spiral motion is generated, as may be seen at any time in the ordinary washbowl. It is, therefore, aside from other proofs, quite safe to assume, when there is an abrupt change of section in a pipe line from a larger to a considerably smaller one, that a similar spiral motion will be set up, and it needs no extended argument to prove that the higher the velocity, the longer the pitch of the spiral, which latter will keep lengthening as the water flows on in a straight pipe, the particles tending continually to move more and more nearly in straight lines. It is well known, further, that velocity head is convertible into pressure head and *vice versa*. It becomes apparent, therefore, that if the pressure head be measured a short distance below a point where a reduction of cross-section of the flowing stream has taken place, we may expect to find that the true velocity of a particle of water, the flow at that point being in a spiral,

will exceed the rectilinear velocity in the direction of the axis, and will also exceed the true velocity further along the pipe where the pitch of the spiral has been increased, whence the pressure head at the up-stream point will be reduced by the excess of velocity head there, and it is entirely possible to conceive, what actually occurs in the Venturi meter, that the following length of pipe might show a gain of pressure rather than the loss to be expected from frictional resistances. This is, apparently, exactly what takes place in the Ogden pipe on which Piezometer No. 4 is 23 ft. down stream from the tunnel mouth where a contraction takes place from a section 9 ft. square to a 6-ft. circular one. The lower the velocity, the shorter the pitch of the spiral. Therefore, at low velocities, the ratio of the true or spiral velocity of the particles to the rectilinear velocity will be much greater than at high velocities; hence the pressure head will be much lower relatively to that at other points, as observed by the authors. The gradual straightening of the spiral results in readings farther down much more nearly in accord with those above and unaffected by the contraction. It may be remarked that this spiral motion, while apparently reducing the loss of head in the section below the contraction, must actually increase it; and a very interesting point is raised as to the rapidity with which the filaments straighten themselves out, or, in other words, how far below a contraction we must go to get a normal pressure reading. The fact that the lower observations, as plotted in Fig. 3, Plate IX, show an excessive loss of head, indicates that a distance of 2 733 ft. in the 6-ft. pipe is not entirely sufficient to hide its effects from observation with the mercurial measuring apparatus used here. How much farther the effect would be noticeable, with a water column or some more delicate apparatus, is an open question. Mr. Williams.

To determine the effect of the tunnel, it is evident that it is not proper to proceed as the authors have done and from the difference shown by Piezometers Nos. 4 and 5 take the computed loss in 67 ft. of stave pipe. The nearest to a correct proceeding, possible with the data at hand, is to take from the loss of head shown between Piezometers Nos. 5 and 3 the loss due to an equal length of stave pipe as deduced from the observations on the long section, when the effect of the tunnel will be seen to follow the same law as that of other resistances to flow, *i. e.*, to increase as the square of the velocity, and not in the manner indicated by the authors upon pages 48 and 49.

On Fig. 4, Plate IX, the result is shown graphically, the abscissas between the lines $O\ A$ and $O\ B$ showing the apparent increased loss of head due to the tunnel. From this it appears that the loss is about 6% greater with the tunnel as it is than it would be with the stave pipe continued through it.

It may be proper to call attention to the fact that in Figs. 1, 2 and 3, Plate IX, the velocity heads are plotted in inches of water, not

Mr. Williams. in feet, as the writer happened to have at hand a transformation curve for velocities to velocity heads in this unit. In Fig. 4, Plate IX, the velocity heads are plotted in feet.

Considering the steel pipe, it appears that the two groups of observations, Nos. 22, 23, 24, 25, 31, 32 and 33, and Nos. 72, 73, 74 and 75, fall very well upon the straight line through the origin, while the others show a higher loss of head than the line fitting the observations named. If we fit a line to the observations from Nos. 18 to 11, as plotted, the observations at the lowest velocities still show losses of head which are too high, so we have either to assume that the loss of head in riveted pipe does not vary as the square of the velocity, or else look for a cause for a low reading in Piezometer No. 1 or a high one in No. 2. The apparently close and accurate instrumental work done by the authors at the other gauges does not give much weight to the probability of errors of observation here, so that the cause is rather to be sought in the line itself. The data published seem hardly sufficient for the case, although the curvature in the line may possibly set up enough spiral flow to cause the lower gauge to read low. The authors themselves are best qualified to discuss this question. As to the possibility that the law in riveted pipe may be more than slightly different from that in cast-iron or wood, it may be said that the observations of Emil Kuichling, M. Am. Soc. C. E., on the Rochester conduits and of Clemens Herschel, M. Am. Soc. C. E., on the East Jersey Water Company's lines, do not indicate anything of the sort, nor do observations upon highly tuberculated pipes, nor, as pointed out previously, those on the tunnel section. The writer, therefore, has come to the conclusion regarding the riveted pipe work, already expressed, that although the observations may be equally accurate, the conditions are not such as to make the results as valuable as are those on the stave pipe.

From the apparent fact that the observations on the short section of stave pipe are influenced by the tunnel effects which are subject to quite wide variation, according as the flow is increased or decreased to produce the velocity under consideration, it seems rather questionable to attempt to determine the effect of age upon the capacity of the conduit by comparisons between the observations in 1897 and those of 1899 on this section. A similar criticism may be made as to the steel pipe, though to a somewhat more restricted degree.

The effect of spiral currents upon the registry of the meters is another interesting consideration. From the velocity head plottings, both in the stave pipe experiments and those on the riveted pipe, which were not simultaneous, it appears that there was a similar irregularity of results with velocity heads between 0.30 and 0.45 in. This, of course, points to a common cause, which seems most likely to be found in the meters. The position of the meters being such that

the water enters by a Y and a curve,* it is easy to conceive that, at some velocities the spiral motion generated at the Y may be reduced by the curve, and at others intensified there, and this might easily account for the irregularity referred to, as a greater or less spiral motion would reduce or increase the difference of head between the inlet and the throat, which seems to indicate that, after all, the Venturi meter, like many another type, is only absolutely reliable when used under exactly the conditions at which it was rated. Mr. Williams.

In this connection it may be well to add that when observations are plotted, as the writer has done in these cases, it is possible and proper to reject inaccurate ones, and to deduce coefficients from the points on the line rather than from the actual observations, thus eliminating, to a large extent, the individual inaccuracies. Having proceeded thus far, it only remains to drop the ancient Chezy and the modern Kutter formulas, and adopt one with an approximately logical foundation, to get the subject of hydraulics into a shape consonant with nineteenth century progress.

George W. Rafter, M. Am. Soc. C. E. (by letter).—This paper is an elegant sequel to the previous one, and presents, in compact form, data of considerable value to hydraulicians. The minute detail with which the authors have described their methods and appliances will be, without doubt, very satisfactory to those who find themselves unable to judge of the value of a paper when presented on the broad lines of useful results, without reference to the methods used in reaching them. The authors are to be congratulated on having given apparently everything necessary for intelligent judgment. Mr. Rafter.

The foregoing reflections are not in any way suggested by deficiencies in the paper, but refer to its minute fulness. As regards hydraulic methods and appliances, every possible question seems to have been answered, thus leaving one free to discuss the broad problem of increase of friction head with advancing age in large riveted steel, wood-stave or other water conduits, and without special reference to the detail of the present experiments, which, taken in conjunction with the authors' previous paper, may be assumed to illustrate the hydraulic conditions of the Ogden pipe in considerable detail.

Broadly, we may assume that many water conduits decrease somewhat in carrying capacity with advancing age. The paper indicates that for the Ogden pipe, this decrease is greater in steel pipe than in wood. Indeed, the wood pipe is shown to have increased in carrying capacity with advancing age. The reasons for these differences are not given, although it seems clear enough that an investigation of flow through a water conduit which reveals such marked changes in carrying capacity, as well as differences between two kinds of pipes, as are here indicated, ought to be accompanied by a study of the causes for such changes and differences.

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* *Transactions*, Am. Soc. C. E., Vol. xxxviii, p. 279.

Mr. Rafter. Engineers sometimes err in not tracing out final causes, especially in cases like the present one where fields of knowledge, outside of engineering pure and simple, require to be traversed in order to reach an adequate solution. Nevertheless, the writer does not criticise the paper because of such omission, but merely mentions it as a suggestion for future work.

In 1891, when the writer presented his paper on "The Hydraulics of the Hemlock Lake Conduit of the Rochester, N. Y., Water-Works,"* drawing the conclusion, from certain discharge measurements made in 1890, that the high values of c in the expression $v = c\sqrt{r\,s}$, previously used in computing flow through large mains, were not justified by the facts, his conclusions as to the relatively low values of c really applying to riveted-steel conduits, were somewhat questioned. Time, however, is a great clarifier, and not only are the writer's views as to the lower values of c now universally admitted, but, since 1891, considerable energy has been expended in showing why, in large steel conduits of some age, it is impossible that any view other than the writer's could possibly apply. On this line, a theory of gradual deterioration has been built up, and many facts have been gathered, tending to substantiate it.

While the writer has no desire to controvert the view that many water conduits have decreased in carrrying capacity with age, he nevertheless wishes to point out that this result is by no means universal—the Ogden wood-stave pipe is a case in point—and that there are undoubtedly a considerable number of water conduits a long time in use, which are to-day discharging at full capacity substantially as much water as when first placed in service.

Speaking broadly, the evidence, as it now stands, apparently indicates that steel-plate conduits are particularly subject to decrease in carrying capacity with increased age. So far as the writer can determine, there seems to be a practical difficulty in coating the built-up-plate conduits, which, in some degree, militates against their usefulness. It is true that coated cast-iron pipes have also shown decrease in carrying capacity, but not, the writer concludes, to such an extent as the wrought-iron or steel-plate conduits.

As regards deficiencies in the coating, the writer is unable to add very much to his discussion of Mr. FitzGerald's paper on "Flow of Water in 48-In. Pipes," presented to the Society in 1896, and it is proposed, therefore, to give here a brief account of what may be termed the biological causes for the decrease in carrying capacity, referred to.

So far as present information goes, difficulties of this sort have been referred to two classes of animal life, namely, fresh-water sponges and fresh-water polyzoa. The fresh-water sponges have been introduced to the Society by Mr. FitzGerald in his two papers, "Spongilla

* *Transactions*, Am. Soc. C. E., Vol. xxvi, p. 13.

in Main Pipes"* and "Flow of Water in 48-In. Pipes,"† but without giving any account of them. So far as the writer now recollects, aside from a brief reference in the discussion of his paper on "The Hydraulics of the Hemlock Lake Conduit of the Rochester, N. Y., Water-Works," the polyzoa have not been considered before this Society as the cause of decrease in carrying capacity of water conduits. Hence, the writer feels justified in giving a brief statement of the habits of the sponges and polyzoa. Mr. Rafter.

Knowledge of the American forms of fresh-water sponges was extended greatly by the monograph‡ of Edward Potts, who has described and figured a considerable number of species, and his paper may be referred to as embodying practically all that we know about the American forms of these interesting animals.

Some of the fresh-water sponges may form incrustations like those described by Mr. FitzGerald in his paper entitled, "Flow of Water in 48-In. Pipes," although, thus far, only one or two species have been certainly identified as offending in these particulars, as, for instance, *Spongilla lacustris* at Boston, and *Meyenia fluviatalis* at Rochester. It is possible that on further study other forms of fresh-water sponge may be found to be giving rise to this trouble, although, aside from one or two forms, such supposition is rendered slightly improbable because close conduits do not seem to be the natural home of many species.

According to Mr. Potts, fresh-water sponges do not differ in constitution and general appearance from marine sponges, except that the fresh-water forms are characterized by the presence of certain seed-like bodies called gemmules or statoblasts, and which are in effect eggs from which new colonies issue. These gemmules are not found in marine sponges.

The gemmules are nearly spherical and about $\frac{1}{50}$ in. in diameter. They are sometimes found floating freely in waters inhabited by fresh-water sponges. As to the methods of germination, Mr. Potts' monograph may be referred to for the detail.

Most of the fresh-water sponges are characterized by a more or less vivid green color, which, however, is not universal, but, according to Mr. Potts, is closely dependent on the quantity or quality of the light received. A sponge which has germinated away from the light will be nearly white, gray or cream colored. If brought into full sunlight, it gradually becomes green, finally attaining a bright vegetable green. Some species, as for instance, *Meyenia leidyi*, are stated to never become green. On this account, *Meyenia leidyi* may be expected to grow in

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* *Transactions*, Am. Soc. C. E., Vol. xv, p. 337.

† *Transactions*, Am. Soc. C. E., Vol. xxxv, p. 241.

‡ "Contribution Towards the Synopsis of the American Forms of Fresh-Water Sponges, with Descriptions of those Named by other Authors in all Parts of the World." by Edward Potts. *Proceedings*, Academy of Natural Sciences of Philadelphia for April-August, 1897.

Mr. Rafter. water conduits, where there is entire absence of light. This species is further characterized by a persistent habit through which the growths of successive seasons rise one above another, forming series of thin laminæ. In this way it sometimes builds up smooth rounded prominences of compact texture. The fact that it is sometimes found at considerable depths, may also be taken to indicate that this species may be found on the interiors of water conduits.

The fact that most of the sponges are naturally of a bright green color must, so far as present information goes, be taken to indicate that their natural habitat is in places sometimes subject to exposure to light, although many of the species undoubtedly prefer subdued light. Professor Lankester has shown the occasional occurrence of chlorophylloid green coloring matter in the tissue of animals, among others in fresh-water sponges, in *Meyenia fluviatalis.* A fact of this character tends strongly to show that the natural habitat is to be found in localities at any rate receiving some light, although it ought not to be overlooked that several species grow in places where the light is subdued. Without going into the subject extensively, the writer will for the present merely state his opinion that this is, with many species, largely a question of convenient attachment to a fixed support, rather than a necessary elementary condition. At any rate, the presence of the chlorophylloid coloring substance, in either plants or animals, implies exposure to light.*

The fresh-water sponges are widely distributed throughout the United States, Mr. Potts stating that he has examined *Spongilla fragilis* from at least 32 localities in 18 States; *Spongilla lacustris* from 26 localities in 16 States; *Meyenia fluviatalis* from 25 localities in 14 States; and *Tubella Pennsylvanica* from 18 localities in 11 States. That the fresh-water sponges are subject to considerable modifications under varying environments is indicated by the statement of Mr. Potts that hardly any two specimens were found exactly alike in their so-called typical features.

The place of the fresh-water sponges, in the animal kingdom, is found in the sub-kingdom, Protozoa. They are, therefore, allied to the Infusoria and the Rhizopods, the lowest forms of invertebrate animals.

The fresh-water polyzoa are a much higher form, being found in the sub-kingdom, Mollusca, and hence related to the Cephalopods, Gastropods, and other relatively advanced forms of the Molluscan sub-kingdom. They possess a complex alimentary system, with an œsophagus, stomach and intestinal tract. They also have a nervous system and well-developed muscles. Some species grow attached, while others are free-floating. Fixed forms are usually found immov-

* For reference to Professor Lankester's determinations of chlorophyl in minute animal forms, see Sacks' "Text Book of Botany," p. 767.

Mr. Rafter.

ably fastened by their ectocysts to the lower surface of submerged stones or floating timbers. In their fully developed state, the polyzoa live in colonies, a large number of individuals, each with its own digestive tube, tentacles, nerve ganglion, muscles, generative organs, etc., each reproducing itself either by gemmation or fixed statoblasts, while all continue organically united in a single group. Reproduction is either by budding or by statoblasts. When from buds, they grow from the side of an adult polypide. Statoblasts may be either fixed or free. The free statoblasts are the founders of new colonies, while buds merely increase the number of individuals in each colony.

Generally, the polyzoa do not thrive in places subject to the direct action of sunlight. Their natural habitat seems to be in dark places. Undoubtedly, some of the species may exist in entire absence of light, although whether they thrive vigorously in such places is not definitely known. *Cristatella* is, however, an exception. According to Professor Alman, this polyzoon delights in exposure to the full influence of the sun, and may be seen basking upon the upper side of submerged stones, or creeping over the stems of aquatic plants in lakes and ponds.* Mr. Hyatt, however, points out that *Pectinatella* apparently prefers strong light in July and August, but cannot stand it at all in October. In the summer months it is found abundantly distributed in exposed shallow waters, but in the fall it disappears from such locations, and can then be discovered only in shaded places several feet below the surface. Colonies of *Pectinatella* frequently grow several feet in diameter.

Many species of the fresh-water polyzoa show considerable color, although not always a chlorophyllaceous green. *Paludicella* is, however, an olive green color. Its single filaments are from $\frac{1}{20}$ to $\frac{1}{30}$ in. in diameter. It is somewhat unlikely that with an olive green color predominant in most normal specimens, the natural habitat is found in absolute darkness. *Fredricella* may be cited as a species which apparently prefers nearly absolute darkness. According to Mr. Hyatt, this form is only found in the darkest places. *Plumatella* is another form apparently preferring light, and which is frequently found growing from the ends of water grasses, without any protection whatever from light and heat.

Aside from the influence of light on the development of color, there are two other facts which tend to show that the fresh-water polyzoa are not likely to grow naturally in water conduits. In searching for them along streams and about ponds, they are only occasionally found in rapidly moving water, their preference being apparently for very slowly moving or quiet water. Nor, have they usually been found in water of more than 3 or 4 ft. in depth, the

* For convenient English literature of the fresh-water polyzoa, refer to "Alman's Fresh-Water Polyzoa," published by the Ray Society, in 1856, and to Hyatt's Observations on the Polyzoa, in *Proceedings* of the Essex Institute, Salem, 1866–68.

Mr. Rafter. under side of a floating plank or timber being usually the best place to find them. It is somewhat doubtful, therefore, if they readily stand heavy water pressure, and, hence, so far as the present information goes, we should only accept well-attested statements as to their presence in pressure conduits.

Another difficulty is as to the method of attachment. With a perfectly smooth interior surface, there is apparently no way by which polyzoa can attach themselves. But if we assume a broken coating with ragged projections, the case becomes very simple. Floating filaments or germinating statoblasts would be easily caught, and large colonies ultimately developed. As regards fresh-water sponges, the conditions of attachment are somewhat similar, although the sponge has a power of secreting a gluey substance with which it attaches itself to stones in running water, and which might enable it to become attached in slowly moving water within a conduit. In the case of the 48-in. pipe examined by Mr. FitzGerald, it appears that there was a break in the coating at nearly every point where a sponge was attached. But whether this was due to the action of the sponge or was the original cause of attachment, is unknown. Reasoning from purely *a priori* considerations, however, it appears somewhat probable that breaks in the coating were the prime cause.

The foregoing very brief account of the fresh-water sponges and polyzoa, in connection with decrease of carrying capacity of water conduits, is sufficient to show that there are several difficulties to be surmounted before a safe theory of deterioration, which shall have universal application, can be successfully formulated. Nevertheless, the writer does not wish to be understood as saying that in some cases decrease in carrying capacity may not proceed from these causes, although, broadly, the evidence is yet too indefinite to form a safe general hypothesis. That is to say, the writer accepts the well-observed special cases, but is not satisfied that the growth of such forms is the universal explanation. The known preference of the polyzoa for slowly moving or quiet water, together with the development of color masses akin to chlorophyl in the fresh-water sponges and possibly, also, in some forms of polyzoa, militates somewhat against the view that they develop other than accidentally under the conditions of rapid movement and absolute darkness prevailing in water conduits.

As regards chlorophyl in these animal forms, it is not believed that it performs quite the same functions that it does in green plants. It is intended to go no further than to state that these animal forms develop a chlorophylloid substance which is undoubtedly dependent upon the quantity of light received. For such forms a water conduit does not appear to be the natural habitat.

Nevertheless, the fact of finding polyzoa attached to the interiors of water conduits, the same as fresh-water sponges, ought not to be

ignored. Very interesting questions are opened up by such a discovery, and some engineer-biologist, endowed with the scientific spirit and a fair stock of patience, has here an opportunity to elucidate a problem which is not only scientifically interesting, but which has very important commercial bearings. But those who have not pursued working biology to some considerable extent may well await, in this matter, the opinion of the qualified expert, because probably in the entire range of science there is no one place where either preconceived opinions, or those founded on insufficient data, are so likely to be modified by study and experience as in considering the different manifestations of life and the modifications to which it is subject, under varying environment. Realizing this truth, the writer, therefore, stands ready, on the presentation of acceptable evidence, to modify whatever in the nature of opinion is here expressed. Mr. Rafter.

GEORGE H. FENKELL, Jun. Am. Soc. C. E. (by letter).—There is little doubt that the authors have obtained for large wood and riveted pipe the most satisfactory set of experiments ever published. The generalized results obtained, however, for 1897 and 1899, show a considerable variation, and it is impossible to ascribe the cause of these discrepancies to the effect of leaks in the apparatus or to anything else connected with the manipulation of the instruments or the readings of the same. Some of the single observations are obviously in error, as will be seen later, but, on the whole, they show very careful work, and most of the discrepancies must be looked for, either in the effect of curvature on the flow, the tunnel, the Venturi meters, or in the reductions of the observations. Mr. Fenkell.

The writer will not attempt to discuss the first three reasons given, but will confine himself entirely to a criticism of the reductions, the results of which the authors have published in Tables Nos. 3 and 4.

A method of judging the relative value of experiments on the flow of water through pipes, and enabling the student to omit such observations as prove to be unreliable, having given the velocity and the loss of head, first proposed by Gardner S. Williams, M. Am. Soc. C. E., and since used by him and Clarence W. Hubbell, Jun. Am. Soc. C. E., on a wide class of work, is used by the writer.

If $v^2 = 2\,g\,h$, $h = \frac{v^2}{2\,g}$ = velocity head = H_v. If, for each given velocity, the velocity head is calculated and is plotted with the loss of head (H_f), or friction, a straight line through the origin should be the resultant, if the loss of head varies as the square of the velocity.

In Figs. 6 and 7, all observations in each series are shown in this manner. It is a well-known fact that the most satisfactory way to study the relations existing between a series of two quantities is by plotting on squared paper; and it is generally customary to average the results thus obtained (if a straight line) by means of a fine thread,

Mr. Fenkell. which can be moved about until the best average seems to have been found. The writer knows of no discussion on this subject, and it seems to have hardly been considered by hydraulic engineers. In this discussion the average line is found by first finding the center of gravity of an entire series, by dividing the sum of the ordinates and the sum of the abscissas by the number of observations. The series is then divided into two parts by the center of gravity. The center of gravity of each of these two parts is found and is plotted on Figs. 6, 7, 8 and 9 with three concentric circles. This method was first suggested to the writer by Mr. C. W. Hubbell. These two points, which are in line with the center of gravity of the entire series, determine the position of the average line, and only in rare instances, with ordinary experiments, would this line pass precisely through the origin.

It is probable, however, that all errors due to observation, personal error of the observer, calibration of instruments and leaks or air bubbles in the gauge connections, are nearly constant for all velocity heads, and hence for all velocities, and if the average line for a series of points is moved parallel to itself until it passes through the origin, it will then be the average line if all errors are eliminated from the observations.

It is also evident, after plotting all points, that a few are in error to such an extent that they had better be dropped entirely. Most of these are mentioned by the authors as being of a doubtful nature, and in Figs. 6 and 7 they are all marked "omit." In the experiments on the wood pipe, for 1897, Manometer 3–4, Observations 35 and 46 are so treated. In the experiments on the wood pipe, for 1899, Manometer 3–4, Observations 35, 36, 50 and 51 were dropped, while with Manometer 5–6 all are considered reliable. Observations 16, 15, 10, 29 and 28 are omitted from the experiments on the steel pipe, for 1897, and Observation 30 from the 1899 experiments. The lines deduced from the reliable points are drawn in Figs. 6 and 7, and their equations are as follows, H_v referring to velocity head and H_f to loss of head per thousand feet, or friction:

Six-Foot Wood Pipe.

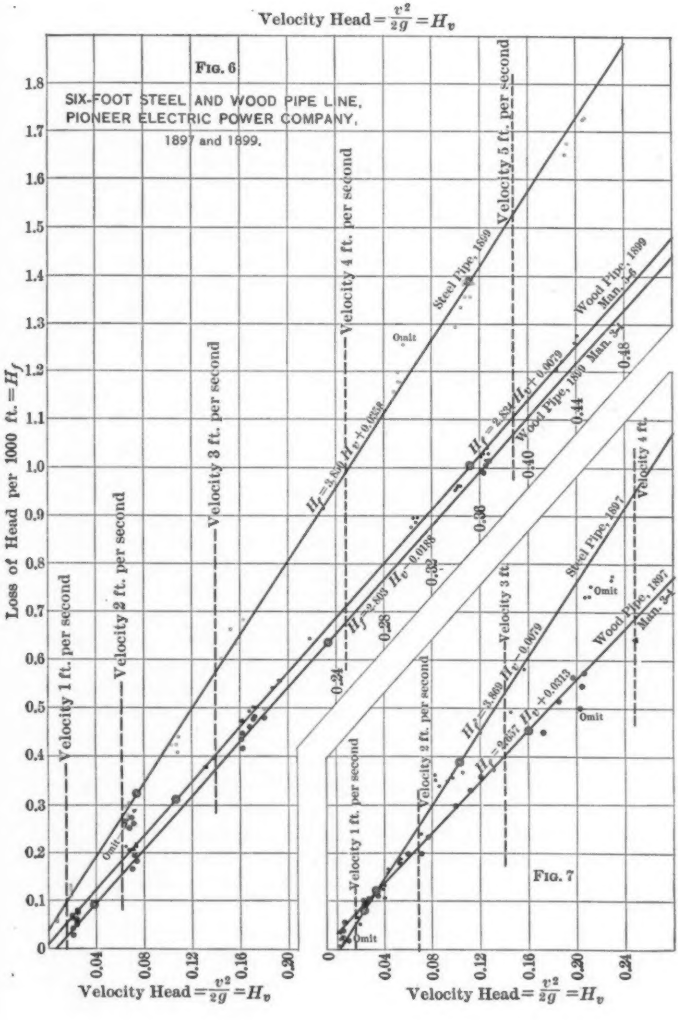
Manometer 3-4, 1897	$H_f = 2.657\ H_v + 0.0313$
" " 1899	$H_f = 2.803\ H_v - 0.0188$
" 5-6, 1899	$H_f = 2.834\ H_v + 0.0079$

Six-Foot Steel Pipe.

Manometer 1-2, 1897	$H_f = 3.869\ H_v - 0.0079$
" " 1899	$H_f = 3.850\ H_v + 0.0358$

These equations are the average lines as plotted, and the constant denotes the distance on the vertical axis that the line passes from the origin. If each one is moved parallel with itself until it passes through the origin, they then drop the constant and become:

Mr. Fenkell.


Velocity Head = $\frac{v^2}{2g} = H_v$
FIG. 6
SIX-FOOT STEEL AND WOOD PIPE LINE,
PIONEER ELECTRIC POWER COMPANY,
1897 and 1899.
Loss of Head per 1000 ft. = H_f
Velocity 1 ft. per second
Velocity 2 ft. per second
Velocity 3 ft. per second
Velocity 4 ft. per second
Velocity 5 ft. per second
Steel Pipe, 1899
$H_f = 3.850\ H_v + 0.0558$
Wood Pipe, 1899 Man. 5-6
$H_f = 2.834\ H_v + 0.0079$
Wood Pipe, 1899 Man. 3-4
$H_f = 2.803\ H_v - 0.0188$
Omit
FIG. 7
Steel Pipe, 1897
$H_f = 3.869\ H_v - 0.0079$
Wood Pipe, 1897 Man. 3-4
$H_f = 2.657\ H_v + 0.0313$
Velocity 1 ft. per second
Velocity 2 ft. per second
Velocity 3 ft.
Velocity 4 ft.
Velocity Head = $\frac{v^2}{2g} = H_v$
Velocity Head = $\frac{v^2}{2g} = H_v$

Mr. Fenkell.

SIX-FOOT WOOD PIPE.

Manometer, 3-4, 1897	$H_f = 2.657\ H_v$
" " 1899	$H_f = 2.803\ H_v$
" 5-6, 1899	$H_f = 2.834\ H_v$

SIX-FOOT STEEL PIPE.

Manometer, 1-2, 1897	$H_f = 3.869\ H_v$
" " 1899	$H_f = 3.850\ H_v$

These equations show the relation existing between the velocity head and the loss of head, and, consequently, with a given velocity, by multiplying its velocity head by the coefficient of H_v, as given in any of the foregoing equations, the result will be the loss of head per thousand feet for that particular pipe. Table No. 8 has been deduced from these equations, and shows the results as compared with those given in Tables Nos. 3 and 4, and the values of c, in the formula $v = c \sqrt{r\, s}$, as compared with those given by the authors.

It is evident that if the straight line passes through the origin, $H_v \propto H_f$. If $v = c \sqrt{r\, s}$, $c = \frac{v}{\sqrt{r\, s}}$. As $v^2 \propto H_f \propto H_v$, and as r is constant for each size, c will remain constant for all velocities in the same pipe, as shown in the table. This method of reducing the observations shows considerable decrease in the carrying capacity of the wood pipe, while that of the steel pipe is slightly increased. This increase is so small, however, that it should not be considered, as it represents a fineness hardly justified by the experiments. It does show, however, that the carrying capacity of the steel pipe, as nearly as can be calculated, was the same in 1899 as in 1897.

Fig. 8 represents the observations on the 38-in. steel conduit, at Rochester, made by Emil Kuichling, M. Am. Soc. C. E., in 1897,* and the writer believes them to be the best experiments on large riveted pipe ever made at low velocities. In Table No. 9 the loss per thousand feet and values of c are compared with those published by Mr. Kuichling. This table was deduced in the same manner as those for the 6-ft. wood and steel pipes.

Fig. 9 shows a few of the results on the East Jersey Water Company's 42-in. riveted pipe,† obtained by Clemens Herschel, M. Am. Soc. C. E. Although a large number of observations were made on this company's conduits, they were taken on so many different lengths, with but few series on the same pipe through a range of velocities, that only a part of them is capable of being worked up in this manner. Many of them show wide discrepancies; that which is shown being the best one published. Fig. 9 also shows, in like manner, the generalized results, taken from an average line, of the experiments

* "Annual Report, Executive Board," Rochester, 1897.

† "115 Experiments on the Carrying Capacity of Large Riveted Metal Conduits. up to 6 ft. per second of Velocity of Flow," by Clemens Herschel, M. Am. Soc. C. E.

Mr. Fenkell.

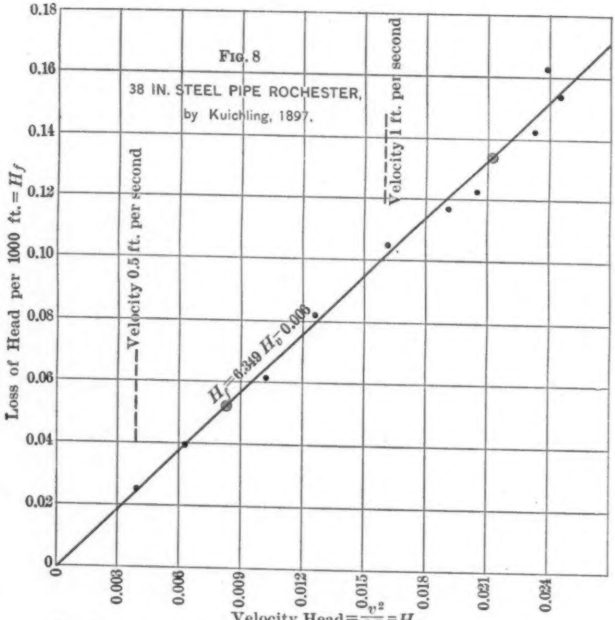


FIG. 8
38 IN. STEEL PIPE ROCHESTER,
by Kuichling, 1897.
Velocity 0.5 ft. per second
Velocity 1 ft. per second
$H_f = 6.349\ H_v - 0.006$
Loss of Head per 1000 ft. $= H_f$
Velocity Head $= \frac{v^2}{2g} = H_v$
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.003
0.006
0.009
0.012
0.015
0.018
0.021
0.024

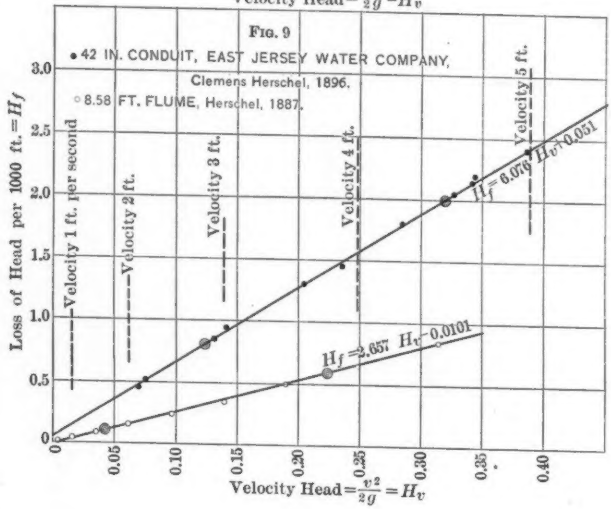


FIG. 9
• 42 IN. CONDUIT, EAST JERSEY WATER COMPANY,
Clemens Herschel, 1896.
○ 8.58 FT. FLUME, Herschel, 1887.
Velocity 1 ft. per second
Velocity 2 ft.
Velocity 3 ft.
Velocity 4 ft.
Velocity 5 ft.
$H_f = 6.076\ H_v + 0.051$
$H_f = 2.657\ H_v - 0.0101$
Loss of Head per 1000 ft. $= H_f$
Velocity Head $= \frac{v^2}{2g} = H_v$
3.0
2.5
2.0
1.5
1.0
0.5
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40

Mr. Fenkell. on an 8.58-ft. flume,* 152.88 ft. long, by Clemens Herschel, M. Am. Soc. C. E. As the single observations were not published, it is impossible to tell the amount of averaging necessary to produce the published results. A comparison of published results and those calculated by the writer on these pipes is shown in Table No. 11.

TABLE No. 8.

Six-Foot Wood Pipe. Generalized Results.

	1897.					1899.					
	Manometer 3-4.					Manometer 3-4.		Manometer 5-6.			
Velocity.	Velocity Head. H_v.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. Table No. 4. H'.	c. From Column 3.	c. From Table No. 4.	Loss per 1 000 ft. H_f.	c. From Column 7.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. Table No. 4. H'.	c. From Column 9.	c. From Table No. 4.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1.0	0.0155	0.041	0.066	127.3	100	0.043	124.5	0.044	0.049	123.2	116.0
1.5	0.0349	0.093	0.123	127.3	110	0.098	124.5	0.099	0.106	123.2	118.7
2.0	0.0621	0.165	0.200	127.3	115	0.174	124.5	0.176	0.184	123.2	119.9
2.5	0.0971	0.258	0.292	127.3	119	0.272	124.5	0.275	0.284	123.2	120.8
3.0	0.1398	0.371	0.400	127.3	122	0.392	124.5	0.396	0.404	123.2	121.4
3.5	0.1902	0.505	0.527	127.3	124	0.533	124.5	0.539	0.548	123.2	121.7
4.0	0.2485	0.660	0.678	127.3	125	0.697	124.5	0.704	0.712	123.2	122.0
4.5	0.3144	....	....	....	....	0.881	124.5	0.891	0.898	123.2	122.2
5.0	0.3882	....	....	....	....	1.088	124.5	1.100	1.105	123.2	122.4
5.5	0.4697	....	....	....	....	1.317	124.5	1.331	1.335	123.2	122.5

Six-Foot Steel Pipe. Generalized Results.

	1897.					1899.			
	Manometer 1-2.					Manometer 1-2.			
Velocity.	Velocity Head. H_v.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. H'.	c. From Column 15.	c. From Table No. 3.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. From Table. No. 3.	c. From Column 19.	c. From Table No. 3.
(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
1.0	0.0155	0.060	0.055	105.5	110	0.060	0.100	105.6	81.6
1.5	0.0349	0.135	0.121	105.5	111	0.134	0.177	105.6	92.0
2.0	0.0621	0.240	0.220	105.5	110	0.239	0.277	105.6	98.0
2.5	0.0971	0.376	0.356	105.5	108	0.374	0.405	105.6	101.3
3.0	0.1398	0.541	0.510	105.5	108	0.538	0.570	105.6	102.4
3.5	0.1902	0.736	0.673	105.5	110	0.732	0.765	105.6	103.2
4.0	0.2485	0.961	0.863	105.5	111	0.957	0.987	105.6	103.8
4.5	0.3144	....	....	....	....	1.210	1.237	105.6	104.3
5.0	0.3882	....	....	....	....	1.494	1.516	105.6	104.7
5.5	0.4697	....	....	....	....	1.808	1.824	105.6	105.0

* *Transactions*, Am. Soc. C. E., Vol. xvii, 1887, and "115 Experiments," by Clemens Herschel.

TABLE No. 9.—Rochester 38-Inch Steel Pipe, 1897. Mr. Fenkell.

Emil Kuichling, M. Am. Soc. C. E.

Velocity.	Velocity Head. H_v.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. Annual Report.	c. From Column 3.	c. From Annual Report.
(1)	(2)	(3)	(4)	(5)	(6)
1.23897	0.02383	0.1513	0.1629	113.2	109.07
1.25425	0.02442	0.1550	0.1545	113.2	113.41
1.22286	0.02322	0.1474	0.1418	113.2	115.41
1.15065	0.02057	0.1305	0.1229	113.2	116.63
1.10751	0.01907	0.1211	0.1172	113.2	114.98
1.02060	0.01618	0.1027	0.1048	113.2	112.03
0.89790	0.01255	0.0797	0.0819	113.2	111.53
0.81413	0.01029	0.0653	0.0615	113.2	116.49
0.63742	0.00630	0.0400	0.0397	113.2	113.66
0.50525	0.00396	0.0251	0.0254	113.2	112.58

TABLE No. 10.—42-In. Conduit, East Jersey Water Company, 1896.

Clemens Herschel, M. Am. Soc. C. E.

No. of Observation.	Velocity.	Weight.	Velocity Head. H_v.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. "115 Exp."	c. From Column 5.
(1)	(2)	(3)	(4)	(5)	(6)	(7)
259...............	2.21	*B.*	0.0758	0.461	0.52	110.1
260...............	3.02	*B.*	0.1416	0.86	0.93	110.1
261...............	3.90	*B.*	0.2362	1.44	1.45	110.1
262...............	4.69	*C.*	0.3403	2.08	2.14	110.1
263...............	4.59	*B*	0.3271	1.99	2.04	110.1
264...............	4.70	*A.*	0.3415	2.08	2.18	110.1
265...............	4.29	*A.*	0.2858	1.74	1.80	110.1
266...............	3.63	*A.*	0.2045	1.24	1.31	110.1
267...............	2.91	*A.*	0.1315	0.80	0.85	110.1
268...............	2.10	*A.*	0.0686	0.42	0.47	110.1
270...............	4.99	*A.*	0.3868	2.35	2.40	110.1

TABLE No. 11.—8.58-Ft. Flume at Holyoke, 1887.

Clemens Herschel, M. Am. Soc. C. E.

No. of Observation.	Velocity.	Velocity Head. H_v.	Loss per 1 000 ft. H_f.	Loss per 1 000 ft. "115 Exp."	c. From Column 4.	c. From "115 Exp."
(1)	(2)	(3)	(4)	(5)	(6)	(7)
501...............	0.5	0.0039	0.0104	0.0078	106.1	126.5
502...............	1.0	0.0155	0.0412	0.0320	106.1	116.6
503...............	1.5	0.0349	0.0927	0.0822	106.1	112.7
504...............	2.0	0.0621	0.1650	0.1532	106.1	110.3
505...............	2.5	0.0971	0.2580	0.2421	106.1	108.8
506...............	3.0	0.1398	0.3714	0.3520	106.1	107.7
507...............	3.5	0.1902	0.5054	0.4902	106.1	106.9
508...............	4.0	0.2485	0.6603	0.6520	106.1	106.2
509...............	4.5	0.3144	0.8354	0.8350	106.1	105.6

Mr. Fenkell. In order to test a set of experiments by this method, it is necessary to have a considerable range of velocities on the same length of pipe, and the first series by the authors was the first set so taken on large stave pipe. Figs. 6 and 7 show the best sets of experiments on large riveted pipe, to date, which can be tested by this method. It is to be regretted that the experiments on the Astoria wooden and riveted pipe, by Arthur L. Adams,* M. Am. Soc. C. E., are not capable of such comparison.

Mr. Henny. D. C. HENNY, M. Am. Soc. C. E. (by letter).—In his discussion of the first series of experiments the writer touched upon some elementary factors which in the first paper had, in his judgment, failed to receive the attention they deserved. Being cognizant of the fact that the first experiments were to be supplemented and extended, he hoped that an opportunity would be sought to remove more fully the doubt which seemed justified regarding some of these points. In this respect, the writer confesses to some disappointment, the more severe as he realizes the scarcity of available information and the perhaps unduly enhanced value which is likely to be accorded to individual experiments.

Diameter.—In the present paper the authors have continued to assume the interior diameter of the stave pipe at 72½ ins. No mention is made of any check, by actual measurement, upon this assumption, which, for reasons stated, the writer considered as probably incorrect. He can now add that, last January, he made a hasty examination of the wooden pipe at the point where it crosses the trestle, at Station 276, at which point Manometer No. 3 was located. He found that while the assumed interior diameter, 72½ ins., corresponds with the projection of thread at each lug of 3¾ ins., the actual projection exceeded this in every case. On a few of the bolts he measured a projection of 8 ins., made possible only by the placing of dozens of washers or fillers under the nuts. Whether the bolts themselves were longer than stated by Mr. Goldmark in his paper† on the Pioneer Power Plant the writer had no means at hand for determining. The exposed portion of the pipe had the appearance of having been re-cinched, after completion, to stop leakage, it being observed incidentally as an interesting fact, that many of the pressed-steel lugs had become badly deformed, the side walls having generally bent inward until in some cases they touched at the top.

The possibility of such reduction in diameter emphasizes the uncertainty, well known to wooden-pipe builders, of basing an estimate of the probable diameter of a stave pipe upon the original width of the individual staves, as appears to have been done by the authors.

It is not contended that the apparent reduction of diameter here

* *Transactions*, Am. Soc. C. E., Vol. xxxvi, p. 1.

† *Transactions*, Am. Soc. C. E., Vol. xxxviii, p. 270.

observed renders a similar excessive reduction likely where the pipe is buried. The probabilities are the other way, yet it leaves it pertinent to ask why the authors have omitted to present measurements of the outer circumference of the pipe, readily obtainable at the various points where the pipe passes over bridges and trestles. Even if such measurements could not be accepted as true averages they would have defined more clearly the relative importance of the possible error due to this cause. The writer believes that at the point examined by him the pipe may well have been less than 71 ins. in diameter, and have had an area close to 5% less than that assumed. Mr. Henny.

It was contended by the authors in their first paper* that there was no need of such measurements: First, because similar uncertainty as to diameter would exist in other stave pipe, which the writer cannot admit, because experience makes it possible, in the construction of stave pipe, to approximate closely to the desired diameters; and second, because the possible error attributed to this cause would be insignificant for the purpose of explaining the disparity in results of the Ogden and previous experiments, which is also objected to as imposing an illogical and irrelevant limitation upon the accuracy of the experiments.

Presence of Air.—The writer has failed to find any information as to the air which had accumulated at summits where it could be blown off. Check valves to be depressed with a bar afforded the only means for releasing air, and these did not occur at all summits, judging from the profile † presented by Mr. Goldmark. In this respect the long section of stave pipe is not as thoroughly protected as the shorter section with the tunnel relief shaft at its upper end. Air at summits, where it cannot be blown off, does not, in the writer's opinion, necessarily reveal its presence through any irregularity in the results of experiments.

Presence of Sediment.—It was considered highly improbable by Mr. Goldmark that sediment could have affected seriously the first experiments on the short section of stave pipe, because the pipe had been in use only a few months previous to the time the experiments were made. This argument does not hold good in the present instance, two years having elapsed. The importance of this matter has become forcibly impressed upon the writer's mind by a recent occurrence which is of interest in this connection.

The light wooden trestle carrying the 52-in. inverted stave-pipe siphon, on the line of the Santa Ana Canal‡ across Deep Cañon, near Redlands, Cal., was originally designed for a load equal to the weight of the pipe and water immediately over it. No account was taken, so far as the writer is aware, of the additional load due to thrust from

* *Transactions*, Am. Soc. C. E., Vol. xl, p. 557.

† *Transactions*, Am. Soc. C. E., Vol. xxxviii, p. 255.

‡ *Transactions*, Am. Soc. C. E., Vol. xxxiii, Plate xvii.

Mr. Henny. vertical curvature, amounting, as was shown in his discussion of the paper mentioned, to over 40% of the load figured on. The trestle settled considerably at the time of filling the pipe, and in the course of years showed further dangerous signs of weakness, until, a short time ago, a portion of it collapsed, carrying a part of the pipe down with it. It then became apparent that, for about 60 ft. in length, the pipe had gradually filled with fine sand, which had become indurated, and which had left only a small passage for the water in the lower reaches of the siphon. The sediment had added to the load, and had probably contributed materially to the disastrous result. So far as this incident concerns the present discussion and the possibility of the formation of sediment in pipe lines generally, it should be understood that during the last three or four years, only a very small flow of water had passed through the pipe, which had thus been converted into a long settling basin; and that the sand-box at the upper end of the canal may not have been effective or properly operated. Yet, considering all circumstances, the probability of a serious amount of sediment forming in this siphon did not seem great.

The Ogden pipe takes water directly from a similar mountain stream; its intake is believed to be unprovided with any sand-trap or settling basin, and the writer understands that the small percentage of the total available power ordinarily utilized calls for only a low velocity in the pipe.

Unless definite information can be presented, tending to prove the pipe to have had a clear section, it is necessary to fall back upon a comparative study of results, and with this end in view Table No. 12 has been deduced.

TABLE No. 12.—Experiments on Six-Foot Stave Pipe.

Group.	Velocity, in feet per second.	Value of c in the Chezy Formula.		
		Short Section.		Long Section.
		1897.	1899.	1899.
		Deduced from average curve.	Calculated from average of observations for each group	
(1)	(2)	(3)	(4)	(5)
J	1.175	104	155	117
N	1.244	106	137	118
L	2.126	116	116	121
I	2.144	116	118	119
K	3.239	123	127	121
M	3.324	123	124	121
T	4.845	....	125	123

Table No. 12 gives the values of *c* for the velocities indicated in Column 2. Column 3 gives these values as deduced from the average curve deduced from the 1897 experiments on the short section of stave pipe. Column 4 gives the values found on the same section of pipe in 1899, and Column 5 gives the values found on the long section of pipe in 1899. Mr. Henny.

The grave disparity which may be observed in the results for low velocities is sufficient to cause their rejection. For velocities above above 1.5 ft. per second the results agree in a satisfactory manner.

As regards the presence of sediment, the comparison gives undoubted weight to the assumption that if no sediment were present in the short section of pipe in 1897, there probably was none in 1899. From the close agreement of the experiments on the short and long section (Columns 4 and 5), the further deduction may be made that the long section must also have been practically free from sediment. The writer believes, however, that this chain of reasoning is not sufficiently strong to depend on for conclusions, where the physical facts in the case, so far as understood by the writer, rather favor the inference that some unknown amount of sediment may have been present in the pipe. Blow-off gates, as argued before, would, upon their first discharge, have afforded the means of establishing the presence or absence of sediment at least at or near the points where attached. If they have been utilized for this purpose the writer has failed to find any mention of it by the authors.

Curvature.—Experiments to determine the effect of sweeping curves upon the loss of head in pipe lines are yet to be undertaken. Measuring the loss of head due to short and sharp curves is not believed to furnish a safe guide in this respect. Short elbows alternating with long tangents in a pipe line are likely to have only a local effect upon the motion of the particles. Skin friction in the straight reaches will tend to oppose the disturbance and will favor, and probably reproduce, approximately parallel and rectilinear motion. With long curves, the centrifugal force, while smaller in amount, has longer time to act and to establish a *régime* of its own for each particular curve, which, whatever it may be, whether a generally rotating motion, or arbitrary eddying, is sure to increase the frictional loss. With comparatively short tangents intervening, the new *régime*, after being established, will extend into the next curve, and be either confirmed or destroyed to make place for another general scheme of movement, and every change of motion involves additional loss.

With a pipe line, such as was available to the authors, having hardly any true tangents, it was impracticable to study the effect of curvature independently. Moreover, it must be admitted that most wooden pipe lines have a considerable percentage of easy curvature. Being familiar with a large number of stave pipe lines now in use, the

Mr. Henny. writer will say, however, that he knows of none where the percentage of true tangents, especially if expressed in diameters, is so small as would appear to be the case with the Ogden pipe line, judging from the plan and profile shown in Mr. Goldmark's paper. And especially is this true if the Ogden pipe line be compared in this respect with stave pipe lines elsewhere, experiments whereon have been recorded. Speculation on this subject may be fruitless, yet it emphasizes the necessity of entering this field analytically before hydraulicians can hope to make material progress.

General Remarks.—The writer wishes to reiterate, that possible presence of air and sediment, as well as probable deficiency in diameter, if causing error at all, have produced cumulative results in increasing the value of c; while an unusually high percentage of length of curves tends in the same direction. Whether the combined effect may be deemed sufficient to bring these experiments in line with those previously undertaken with smooth surfaced conduits of various classes, or whether a serious doubt should be entertained as to the accuracy of the Kutter formula as applied to smooth-bore pipe, can hardly be settled satisfactorily until additional light be thrown upon this complex subject. In the absence of additional and convincing information to the contrary, the writer inclines to the former proposition. Moreover, the new experiments on the stave pipe, taken by themselves, constitute a forcible confirmation of the accuracy of the Kutter formula so far as it accounts for change in velocity.

The experiments on the steel pipe strengthen the belief that the Kutter formula offers no advantage over the simple Chezy formula.

On the important subject of effect of time on the carrying capacity, the experiments shed some valuable light. Table No. 4 is, in this respect, not as conclusive as Table No. 12, since the latter permits of a comparison of the experiments of 1897 and 1899 on the same section of stave pipe. The value of c shows no diminution during the two years' interval. With the steel pipe, the diminution in carrying capacity is very marked, considering the short time the pipe has been in use, and while the earlier experiments indicate a superiority in the carrying capacity of stave pipe over steel pipe, of about 12% for $3\frac{1}{2}$ ft. velocity, this difference appears to have increased, in the course of two years, to 20 per cent.

Mr. Sherman. Charles W. Sherman, Jun. Am. Soc. C. E. (by letter).—Mr. Rafter's discussion on the effect of animal and vegetable life on the discharging capacity of a pipe is very interesting, but needs to be supplemented by records of actual observation of the presence or absence of such growths. The writer submits these few lines in the hope of adding his mite to the meager data on this subject.

Late in the year 1894, a 36-in. force main was laid from the Chestnut Hill Pumping Station to the Fisher Hill Reservoir of the Boston

Water-Works, the distance being something over a mile. Early in the following year, during a test of the new Leavitt pumping engine, observations of the loss of head were taken at three points in a length of about 5 000 ft., from which it was found that the coefficient c of the Chezy formula was 136, v being 4.7 ft. per second, or about what would be expected for a new cast-iron pipe of this size. A year later, or early in 1896, an extensive series of experiments on the friction loss in this pipe was made by the writer, under the direction of Desmond FitzGerald, Past-President, Am. Soc. C. E., with velocities ranging from 1.1 to 4.5 ft. per second. It was supposed that the pipe was in about the same condition, but the results showed a coefficient of about 113, a great loss within a single year. This result was so far from that expected that the pipe was partly drained, and entered at the upper end. Only a small amount of tuberculation was found, but the whole interior surface was covered with a slimy substance which proved upon examination to consist almost wholly of the polyzoon *Fredericella*. In 1897, another experiment, in which v was 3.2 ft. per second, showed c to be about 114. It thus appears that there was a great change in the capacity of the pipe in the first year after it was laid, and practically none in the year following. Mr. Sherman.

Late in 1897, this pipe was cut into, for the purpose of making connections near the pumping station, and an examination of the interior surface at this point showed that practically the same conditions obtained. If anything, the organic growth was somewhat thicker, as was to be expected, this being nearer the source of the food supply.

It seems to the writer that, with New England surface waters, which contain more or less organic matter, such as algæ, to furnish food for them, growths of polyzoa on the interior of the pipes are to be expected, and the result will be a large diminution of the capacity of the pipes within the first year. After that there will be a further gradual diminution of capacity due to the slow increase of tuberculation. With ground-waters or filtered waters, which have not been exposed to the light, such growths will probably not occur, as food for the polyzoa will be lacking. The experience in Brookline, which has a ground-water supply, and where such growths have not been observed, seems to bear out this opinion.

The writer is very glad that Professor Williams has drawn attention to the necessity for some criterion other than the reputation of the experimenter, and the apparent accuracy as indicated by the method of least squares, to give some indication of the reliability of experiments. The method used by Professor Williams and Mr. Fenkell is, doubtless, of great value, as indicating what experiments of any series should be rejected. It involves, however, both a needless assumption and an unnecessary amount of work in its application. If the

Mr. Sherman. logarithms of the velocities be plotted as abscissas, with the logarithms of losses of head as ordinates, a straight line can then be drawn to represent the plotted points, without the laborious computation of, or even the necessity of taking from a diagram, the values of $\frac{v^2}{2g}$, or the "velocity head." By the use of logarithmic cross-section paper, this plotting can be done with great rapidity.

An especial advantage of this method is that it does not require the assumption that the loss of head varies as the square of the velocity: It is assumed only that this loss varies as some unknown power of the velocity. The criterion, that is, the comparison of plotted points with the line representing the series, is similar to that proposed by Professor Williams.

This application of the logarithmic diagram is not new. As far as the writer knows, it was first introduced to this Society by Desmond FitzGerald, M. Am. Soc. C. E., in his paper on "Flow of Water in 48-In. Pipes."* Mr. FitzGerald refers to a paper before the Royal Society for the origin of this method. To be sure, it is not there noted particularly that this furnishes a criterion for the acceptance or rejection of particular experiments in a series, as the method is used in the derivation of an exponential formula. The advantage of the logarithmic diagram over that obtained by plotting "velocity heads" can, perhaps, be expressed no better than in Mr. FitzGerald's words, "Resistances do not vary exactly as the square of the velocity, however much the text books may insist to the contrary."

Mr. FitzGerald. DESMOND FITZGERALD, Past-President, Am. Soc. C. E. (by letter).—The writer has yet to see a structure for conveying water which will have the same capacity after it has been some time in service as it had when new. There may be some material which will not change its character, and upon which animal or vegetable life will not grow, but the writer has not met with such material in his experience. It is, however, extremely dangerous to generalize in engineering matters. There are hardly two waters exactly alike in chemical composition, and serious mistakes may be made by applying the results of experience from a soft New England water to a hard, lime-carrying western water. The writer has often been informed that certain structures for conveying water have as large capacity at the end of several years as they had when new, but closer examination has shown that the data were not sufficiently accurate to settle the question.

The experiments made on large pipes, under the direction of the writer, have already been referred to by Mr. Charles W. Sherman, so that it is unnecessary to say much more in regard to them, except to add that the water was measured carefully by weir, that the losses of head were ascertained from observations on extremely accurate mer-

* *Transactions*, Am. Soc. C. E., Vol. xxxv, p. 241.

cury gauges, and that proper corrections were made in working out the results. Mr. FitzGerald.

The writer has also made experiments on the flow of water through cement-lined pipes, and has been very much surprised to find that there were large frictional losses, almost as great as those arising from old cast-iron pipes, and the only way he can account for this is that even cement-lined pipes do not remain perfectly clean for an indefinite time.

For many years the writer has had charge of the Cochituate and Sudbury Aqueducts and of the determination of their capacities, and he has been very much impressed with the effect on the flow of the water due to slimy growths on the surface of the brickwork. In the case of the Cochituate Aqueduct, if the deposits of slime and dirt are allowed to collect on the interior, they gradually give place to growths of Spongilla, and if these are allowed to accumulate, after a year or two, they become very hard, with long finger-like growths, which are serious obstructions to the flow. With changes of flow, this accumulated dirt on the walls of the aqueduct affects the quality of the water, so that, aside from the question of friction, there is also the important question of the effect on the quality.

In the case of the Sudbury Aqueduct, it has been found that, if the surface of the brick-work is not cleaned, in the course of a year it may accumulate sufficient slime to diminish the maximum capacity about 10 per cent. Some years ago the writer devised a method of cleaning, by a machine which worked under a pressure of water. The machine was carried on wheels with wooden tires, was provided with rotary brushes for cleaning the sides and bottom of the aqueduct, and worked very effectively. A movable shield in front held the water back so as to give the power. The machine was arranged to clean to a height of about 4 ft. only, and since it has become necessary to run larger quantities of water in the aqueduct, the machine has been taken out, and the whole length is now cleaned by hand. This is accomplished by a number of gangs of men, provided with rubber boots, stable and rattan brooms, and reflectors. It takes about nineteen men to clean a mile of aqueduct in a day.

Current meter observations have been taken on the flow in the Sudbury Aqueduct, and the results have been extremely accurate and satisfactory. On April 4th, 1899, with a flow of 74 000 000 galls. daily, the capacity of the aqueduct was only 92.58% of the tabulated capacity, and after cleaning on May 29th, at which time 95 000 000 galls. per day were flowing, the capacity was 103.95% of the tabulated capacity. It is possible that, where an aqueduct has been for a long time in use without cleaning, this decrease in carrying capacity may be found to be even greater than 10 per cent. The writer believes that the facts just cited are sufficient to demonstrate the commercial

Mr. FitzGerald. advantages, under some conditions, of keeping an aqueduct clean, as, for instance, when its full capacity is likely to be taxed.

Mr. Kuichling states that vegetable and animal growths are not often found on the bottoms of pipes, and this agrees with the observations of the writer, but the latter has seen the invert of the Sudbury Aqueduct almost completely covered with a thick growth of sponge.

Mr. Meem has stated that "This doubtless shows that organisms require more, as Mr. Whipple suggests, than that their food be brought to them, and they must also have a 'lodging place,' which is probably furnished in the steel and iron pipes by the commencement of rust." In connection with this matter, the writer desires to state, that the growths all around the interior of the new cast-iron pipes already alluded to, were in the nature of a greasy scum, and, that when this was washed off, the coating of the pipe underneath was as bright as when first laid.

The writer recently had occasion to lay a cast-iron pipe having a diameter of 61½ ins., and 1 800 ft. in length, as an inverted siphon. The reason for using this odd size was that it was found more economical to use the outside moulds already prepared for making a thick 5-ft. pipe, and to produce the thinner pipe, desired for the light pressures at the siphon, by increasing the size of the core. Every effort was made to lay this pipe with great care and to make very tight joints. Under careful test the leakage was found to average only 12 galls. per day for the whole length of the pipe, or 0.005 gall. per day per foot of joint. The interior portions of the joints were filled with Portland cement flush with the pipe and finished very smooth. The pipe was also given an extra painting. In this connection, it may be interesting to note that the average leakage per day per foot of joint from the 48-in. distribution pipes recently laid by the Metropolitan Water-Works was about 5 galls. per day per foot of joint.

The results of some experiments made to determine the carrying capacity of this siphon pipe gave a value of c, in the Chezy formula, of 149.6 for a velocity of 4.65 ft. per second and 154.3 for a velocity of 6.51 ft. per second. The writer believes that this coefficient, 154.3, is the highest ever recorded for cast-iron pipe, but there is no doubt in his mind that in the course of about twenty years this will be reduced by tuberculation to 100.

Messrs. Marx, Wing and Hoskins. CHARLES D. MARX, M. Am. Soc. C. E.; CHARLES B. WING, Assoc. M. Am. Soc. C. E., and LEANDER M. HOSKINS, Esq. (by letter).—It seems unnecessary to add to the discussion of the degree of reliability of the results, already given by the writers, in the paper on the experiments of 1897.

The questions raised by Mr. Henny have already been answered so far as the writers are able to answer them. It is possible that they underestimate the importance of exterior measurements of the pipe

Messrs. Marx, Wing and Hoskins.

at the trestles. If so, it is to be regretted that Mr. Henny did not make as complete a set of such measurements as seemed to him desirable. The writers are informed by Chief Engineer Bannister that many measurements of the interior diameter were made after the pipe was built, and that no appreciable departure from the estimated size was found. The writers certainly have no interest in maintaining that wood pipe offers greater resistance to flow than smooth iron pipe. Neither are they in possession of the data requisite for deciding the question. They do, however, feel warranted in the belief that the *a priori* estimates of the capacity of large stave pipes which have been published by some writers are far too great.

It is hard to believe that the elaborate discussions of Mr. Williams and Mr. Fenkell are intended as serious contributions to hydraulic literature. Certainly, no competent engineer is likely to regard seriously the proposition that many "supposedly reliable observations" are proved to be "nothing more than crude approximations," by the fact that they fail to show losses of head varying as the square of the velocity. Neither will conclusions which are based upon this "criterion," as to the change in capacity of the Ogden conduit, or as to the value of the results presented in the paper, be likely to meet with acceptance.

The supposition that the passage of water from the 9-ft. tunnel into the 6-ft. pipe generates a spiral motion sufficient to seriously affect the pressure readings at Station 4, 23 ft. from the tunnel, and to be noticeable even at Station 3, 2 733 ft. from the tunnel, does not appear to the writers to be intrinsically probable, or to be supported by the gauge readings at Stations 3 and 4.

As the discussion brings out somewhat diverse views upon the question of the change of capacity of the conduit between the dates of the two series of experiments, it may be well to refer again to this question.

In the discussion of the degree of reliability of the first series of results,* the fact was emphasized that it is impossible to determine very precise values of the coefficient c for low velocities, the reason being that a given error in the measurement of pressure causes an error in the estimated value of c which is far greater at low than at high velocities. While fully realizing this fact, it was thought best to extend the observations to as low velocities as practicable, not only because it was hoped that these observations might not be wholly without value in themselves, but because of the desirability of comparison with the results recorded by others, many of which, particularly upon stave pipes, have been made at low velocities. It appears, however, to be unsafe to base conclusions as to change of capacity upon the results obtained at velocities less than about 2 ft. per second.

* *Transactions*, Am. Soc. C. E., Vol. xl, p. 560.

Messrs. Marx, Wing and Hoskins.

As regards the steel pipe, the observations of 1899 probably show, with a somewhat higher degree of precision than the earlier series, the law of variation of loss of head with velocity. It is believed, however, that both series of results for the higher velocities may be accepted for the purpose of making a fairly correct estimate of the change in capacity of the pipe. The results shown in Table No. 3 indicate that the loss of head for a given velocity was about 13% greater in June, 1899, than in August, 1897.

Turning next to the wood pipe results, it must be remembered that the curve of loss of head for the experiments of 1899, shown on Plate VIII, is based wholly upon the observations on the long section of pipe above the tunnel, so that the two curves shown are not directly comparable for the purpose of estimating change of capacity. It cannot be assumed that the two portions of pipe should give identical values of the loss of head per thousand feet of length, especially when the different conditions of curvature are considered. The observations of 1899 on the short section of pipe are not sufficiently numerous to be made the basis of conclusions as to change of capacity. They do, however, show a fair agreement with the results of 1897, the only exceptions to this statement being Groups J and N, both taken at low velocities. The conclusions that appear to be warranted are:

(1) That the capacity of the short section of wood pipe changed only slightly, if at all, during the interval between the two series of experiments; and

(2) That in 1899 there was no important difference in capacity between the two portions experimented on.

The question, suggested by the writers and further referred to by Mr. Kuichling, as to whether the loss of head in the Venturi meters may not have increased, appears not to admit of a certain answer. Some light is perhaps thrown on the question by considering how the general results must be corrected if it be assumed that there has been an increased loss of head in the Venturi proper. This assumption would require the estimated velocities to be decreased, thus increasing the value found for the loss of head at any given velocity. This would imply a greater diminution of capacity of the steel pipe than above estimated, with a like result for the wood pipe. Attention has already been called (page 52) to the fact that if it be assumed that the observed increase in the loss of head between the first and third columns of the difference gauge is chargeable wholly to the part of the pipe between the throat and the down-stream section, this increase agrees well with that computed for the 6-ft. steel pipe. The most probable view appears to the writers to be that the Venturi meter coefficient remained practically constant.

The suggestion that the registration of the meters should be tested might well have been accompanied by a suggestion of specific

means of accomplishing it. No practicable method occurred to the writers. Messrs. Marx, Wing and Hoskins.

Regarding the desirability of examining the interior surface of the conduit, it should be said that the commercial operation of the plant does not admit of a shut-down of sufficient length of time to permit of draining the one mile of steel pipe, much less the five miles of wood pipe, unless damage to the plant should necessitate such draining.